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The Geodesist's Handbook 2020

International Association of Geodesy

A constituent Association of the

International Union of Geodesy and Geophysics (IUGG)

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THE GEODESIST'S HANDBOOK 2020

Table of Contents

Global Geodetic Observing System (GGOS)

IAG Scientific Services

General Information

Foreword

Markku Poutanen[1] · Szabolcs Rózsa[2]

The Geodesist's Handbook is published by the International Association of Geodesy (IAG) periodically after each IUGG/IAG General Assembly. The objective is to present the current IAG structure and its specifications, and to introduce the terms of reference and the officers of the Association's components for the upcoming legislative period to the broad geodetic community. The scientific program and planned activities are described in detail.

The first part of the Handbook 2020 presents the historical developments and current regulations of the IAG (Statutes, Bylaws and Rules as reviewed during the IUGG/IAG General Assembly 2019).

The second part summarises the outcome of the IAG General Assembly held in conjunction with the 27th IUGG General Assembly in Montreal, Canada, in July 2019. An overview of the most important IAG results from 2015 to 2019 is given in the presidential address. The citations of the scientists decorated in Montreal with the highest IAG awards (Levallois Medal, Guy Bomford Prize, and Young Authors Award) are published. Reports of the Secretary General, the IAG Council and Executive Committee meetings, and the IUGG and IAG resolutions conclude this section.

The third part of the Handbook contains the detailed structures and programs for the period 2019-2023. All IAG components (Commissions, Inter-commission Committee, Communication and Outreach Branch, Services, and the Global Geodetic Observing System) are presented along with their sub-components (Sub-commissions, Projects, Study Groups and Working Groups). This part describes the planed scientific work of IAG during the coming years.

The fourth part completes the Handbook with some general information useful for the geodetic community. The IAG Internet representation and the publication series are highlighted, and the IAG national delegates and representatives to services and international scientific bodies are listed.

We thank the contributors to the Geodesist's Handbook 2020. These are in particular all the IAG officers listed in the structures, but also the uncounted secretaries and technicians in the institutions affiliated with IAG or one of its components and sub-components. The engaged and authentic cooperation in geodesy is one of the most effective means for the great success of our science. We hope that this collaboration will be continued or even extended in the current period 2019-2023.

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List of previous Geodesist's Handbooks

1980: Bulletin Géodesique, Vol. 54, No. 3, http://link.springer.com/journal/190/54/3/page/1

1984: Bulletin Géodesique, Vol. 58, No. 3, http://link.springer.com/journal/190/58/3/page/1

1988: Bulletin Géodesique, Vol. 62, No. 3, http://link.springer.com/journal/190/62/3/page/1

1992: Bulletin Géodesique, Vol. 66, No. 2, http://link.springer.com/journal/190/66/2/page/1

1996: Journal of Geodesy, Vol. 70, No. 12, http://link.springer.com/journal/190/70/12/page/1

2000: Journal of Geodesy, Vol. 74, No. 1, http://link.springer.com/journal/190/74/1/page/1

2004: Journal of Geodesy, Vol. 77, No. 10-11, http://link.springer.com/journal/190/77/10/page/1

2008: Journal of Geodesy, Vol. 82, No. 11, http://link.springer.com/journal/190/82/11/page/1 (open access)

2012: Journal of Geodesy, Vol. 86, No. 10, http://link.springer.com/journal/190/86/10/page/1 (open access)

2016: Journal of Geodesy, Vol. 90, No. 10, https://link.springer.com/journal/190/90/10/page/1 (open access)

The International Association of Geodesy

Historical Overview

H. Drewes[1] · **J. Adám**[2] · **M. Poutanen**[3]

The history of the International Association of Geodesy goes back to April 1862 when the Central European Arc Measurement ("Mitteleuropäische Gradmessung") was initiated at a "preliminary consultation" of representatives of the states of Prussia, Austria and Saxony in Berlin. At the end of the year, 16 countries had joined the project. The first General Conference was held in Berlin, October 1864, with delegates from 14 countries. In 1867 it was expanded to the European Arc Measurement and in 1886 to the International Geodetic Association ("Internationale Erdmessung", "Association Géodésique Internationale"). At the Constitutive Assembly of the International Research Council (IRC) in Brussels, July 1919, the "Section Geodesy" was one of the constituents of the International Union of Geodesy and Geophysics (IUGG) and held its Constitutive Assembly during the first IUGG General Assembly in Rome, April-May 1922. The name was changed to "Association of Geodesy" in Stockholm, August 1930, and to the present name in July 1946. The following summarises the historic development.

Table 1 General Conferences / General Assemblies of the International Association of Geodesy and predecessors

No	*Venue*	*Year*
I. General Conferences		
Ia. Mitteleuropäische Gradmessung - Central European Arc Measurement (1862-1867)		
1	Berlin, Prussia	1864
2	Berlin, Prussia	1867
Ib. Europäische Gradmessung - European Arc Measurement (1867-1886)		
3	Vienna, Austria-Hungary	1871
4	Dresden, German Empire	1874
5	Stuttgart, German Empire	1877
6	Munich, German Empire	1880
7	Rome, Italy	1883
8	Berlin, German Empire	1886
Ic. Internationale Erdmessung - Association Géodésique Internationale – Int. Geodetic Association (1886-1922)		
9	Paris, France	1889
10	Brussels, Belgium	1892
11	Berlin, German Empire	1895
12	Stuttgart, German Empire	1898
13	Paris, France	1900
14	Copenhagen, Denmark	1903
15	Budapest, Austria-Hungary	1906
16	Cambridge, United Kingdom	1909
17	Hamburg, German Empire	1912
II. General Assemblies of the Section and Association of Geodesy at the General Assemblies of the IUGG		
IIa. IUGG Section of Geodesy (1919-1930)		
18	Rome, Italy (Constitutive Assembly)	1922
19	Madrid, Spain	1924
20	Prague, Czechoslovakia	1927
21	Stockholm, Sweden	1930

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Table 1 continued

No	Venue Participants:	Year	IUGG	IAG
IIb. IUGG Association of Geodesy (1930-1946)				
22	Lisbon, Portugal	1933	200	90
23	Edinburgh, UK	1936	344	91
24	Washington, USA	1939	805	86
IIc. IUGG International Association of Geodesy (1946-…)				
25	Oslo, Norway	1948	368	
26	Brussels, Belgium	1951	918	134
27	Rome, Italy	1954	923	235
28	Toronto, Canada	1957	1165	218
29	Helsinki, Finland	1960	1375	345
30	Berkeley, USA	1963	1938	329
31	Zurich/Lucerne, Switzerland	1967	2200	357
32	Moscow, USSR	1971	2577	449
33	Grenoble, France	1975	2564	398
34	Canberra, Australia	1979	1944	278
35	Hamburg, F.R. Germany	1983	3204	472
36	Vancouver, Canada	1987	3939	420
37	Vienna, Austria	1991	4331	594
38	Boulder, USA	1995	4481	567
39	Birmingham, UK	1999	4052	478
40	Sapporo, Japan	2003	4151	407
41	Perugia, Italy	2007	4351	433
42	Melbourne, Australia	2011	3392	370
43	Prague, Czech Republic	2015	4231	534
44	Montreal, Canada	2019	3715	465
45	Berlin, Germany	2023		

Table 2 Scientific Assemblies of the International Association of Geodesy

No	Venue	Date	Number of Attendees
1	Tokyo, Japan	May 7-15,1982	200
2	Edinburgh, UK	August 3-12,1989	355
3	Beijing, China	August 8-13,1993	340
4	Rio de Janeiro, Brazil	September 3-9,1997	250
5	Budapest, Hungary	September 2-7, 2001	461
6	Cairns, Australia	August 22-26, 2005 (joint with IAPSO and IABO)	IAG: 145 (in all: 724)
7	Buenos Aires, Argentina	August 31- Sept. 4, 2009	363
8	Potsdam, Germany	September 1-6, 2013	538
9	Kobe, Japan	July 30 – August 4, 2017 (joint with IASPEI)	IAG: 361 (in all: 1107)
10	Beijing, China	June 28 – July 3, 2021	

Table 3 Presidents of the International Association of Geodesy and predecessors

No	Period	Position	Name	Residence
Ia. Mitteleuropäische Gradmessung (1862-1867), Europ. Gradmessung (European Arc Measurement) (1867-1886)				
1	1864 – 1868	President of the Permanent Commission	*Peter Andreas Hansen*	Gotha, Thuringia
2	1869 – 1874	President of the Permanent Commission	*August von Fligely*	Vienna, Austria-Hungary
3	1874 – 1886	President of the Permanent Commission	*Carlos Ibañez de Ibero*	Madrid, Spain
Ib. Internat. Erdmessung - Association Géodésique Internationale (International Geodetic Association) (1886-1917)				
3	1887 – 1891	President of the Association	*Carlos Ibañez de Ibero*	Madrid, Spain
4	1892 – 1902	President of the Association	*Hervé A. E. A. Faye*	Paris, France
5	1903 – 1917	President of the Association	*Léon J. A. Bassot*	Paris, France
Ic. Reduced Geodetic Association among Neutral States (1917-1922)				
6	1917 – 1922	President of the Reduced Association	*Raul Gautier*	Geneva, Switzerland

Table 3 continued

No	*Period*	*Position*	*Name*	*Residence*
IIa. IUGG Section of Geodesy (1919-1930)				
7	1922 – 1933	President of the Section	*William Bowie*	Washington, USA
IIb. IUGG Association of Geodesy (1930-1946)				
8	1933 – 1946	President of the Association	*Felix A. Vening-Meinesz*	Amersfoort, The Netherlands
IIc. International Association of Geodesy (IAG) of the IUGG (1946-…)				
9	1946 – 1951	President of the IAG	*Walter D. Lambert*	Washington, USA
10	1951 – 1954	President of the IAG	*Carl F. Bäschlin*	Zurich, Switzerland
11	1954 – 1957	President of the IAG	*James de Graaf Hunter*	London, United Kingdom
12	1957 – 1960	President of the IAG	*Gino Cassinis*	Milan, Italy
13	1960 – 1963	President of the IAG	*Charles A. Whitten*	Washington, USA
14	1963 – 1967	President of the IAG	*Guy Bomford*	London, United Kingdom
15	1967 – 1971	President of the IAG	*Antonio Marussi*	Trieste, Italy
16	1971 – 1975	President of the IAG	*Youri D. Boulanger*	Moscow, USSR
17	1975 – 1979	President of the IAG	*Tauno J. Kukkamäki*	Helsinki, Finland
18	1979 – 1983	President of the IAG	*Helmut Moritz*	Graz, Austria
19	1983 – 1987	President of the IAG	*Peter V. Angus-Leppan*	Kensington, Australia
20	1987 – 1991	President of the IAG	*Ivan I. Mueller*	Columbus, USA
21	1991 – 1995	President of the IAG	*Wolfgang Torge*	Hannover, Germany
22	1995 – 1999	President of the IAG	*Klaus-Peter Schwarz*	Calgary, Canada
23	1999 – 2003	President of the IAG	*Fernandó Sansó*	Milan, Italy
24	2003 – 2007	President of the IAG	*Gerhard Beutler*	Bern, Switzerland
25	2007 – 2011	President of the IAG	*Michael G. Sideris*	Calgary, Canada
26	2011 – 2015	President of the IAG	*Chris Rizos*	Sydney, Australia
27	2015 – 2019	President of the IAG	*Harald Schuh*	Potsdam, Germany
28	2019 – 2023	President of the IAG	*Zuheir Altamimi*	Paris, France

Table 4 Permanent Secretaries / Secretaries General of the International Association of Geodesy and predecessors

No	*Period*	*Position*	*Name*	*Residence*
Ia. Internationale Erdmessung - Association Géodésique Internationale (International Geodetic Association) (1886-1917)				
1	1886 – 1900	Permanent Secretary	*Adolf Hirsch*	Neuchatel, Switzerland
2	1900 – 1921	Permanent Secretary	*H. G. van de Sande-Bakhuysen*	Leiden, The Netherlands
Ib. IUGG Section of Geodesy (1919-1930) and IUGG Association of Geodesy (1930-1946)				
3	1922 – 1946	Secretary General	*Georges Perrier*	Paris, France
Ic. International Association of Geodesy of the IUGG (1946-…)				
4	1946 – 1960	Secretary General	*Pierre Tardi*	Paris, France
5	1960 – 1975	Secretary General	*Jean-Jacques Levallois*	Paris, France
6	1975 – 1991	Secretary General	*Michel Louis*	Paris, France
7	1991 – 1995	Secretary General	*Claude Boucher*	Paris, France
8	1995 – 2007	Secretary General	*Carl Christian Tscherning*	Copenhagen, Denmark
9	2007 – 2019	Secretary General	*Hermann Drewes*	Munich, Germany
10	2019 – 2023	Secretary General	*Markku Poutanen*	Masala, Finland

Table 5 Central Bureau (since 2007 Office) of the International Association of Geodesy and predecessors

No	*Period*	*Host Institute*	*Name of Director*	*Residence*
1	1864 – 1885	Royal Prussian Geodetic Institute	*Johann Jacob Baeyer*	Potsdam, Prussia
2	1886 – 1917		*Friedrich Robert Helmert*	Potsdam, Germany
3	1917 – 1922		*J. H. Louis Krüger (p.p.)*	Potsdam, Germany
4	1922 – 1946	Institut Géographique National (IGN)	*Georges Perrier*	Paris, France
5	1946 – 1960		*Pierre Tardi*	Paris, France
6	1960 – 1975		*Jean-Jacques Levallois*	Paris, France
7	1975 – 1991		*Michel Louis*	Paris, France
8	1991 – 1995		*Claude Boucher*	Paris, France
9	1995 – 2007	Niels Bohr Institute, Department of Geophysics, University of Copenhagen	*Carl Christian Tscherning*	Copenhagen, Denmark
10	2007 – 2019	Deutsches Geodätisches Forschungsinstitut	*Hermann Drewes*	Munich, Germany
11	2019 – 2023	Finnish Geospatial Research Institute (FGI)	*Markku Poutanen*	Masala, Finland

Table 6 Editors in Chief of Official Journals of the International Association of Geodesy and predecessors

No	*Journal*	*Period*	*Name of Editor-in-Chief*	*Residence*
I.1	Bulletin Géodésique	1922 – 1945	*Georges Perrier*	Paris, France
I.2		1946 – 1951	*Pierre Tardi*	Paris, France
I.3		1952 – 1964	*Jean-Jacques Levallois*	Paris, France
I.4		1965 – 1975	*Michel Louis*	Paris, France
I.5		1975 – 1986	*Ivan I. Mueller*	Columbus, USA
I.6		1987 – 1995	*Carl Christian Tscherning*	Copenhagen, Denmark
II.1	Manuscripta Geodaetica	1976 – 1980	*Ivan I. Mueller*	Columbus, USA
II.2		1980 – 1982	*Peter Meissl*	Graz, Austria
II.3		1982 – 1988	*Erwin Groten*	Darmstadt, F.R. Germany
II.4		1989 – 1991	*Clyde C. Goad* *Erik W. Grafarend*	Columbus, USA Stuttgart, Germany
II.5		1991 – 1995	*Petr Vaniček*	New Brunswick, Canada
III.1	Journal of Geodesy	1995 – 2003	*Peter J. G. Teunissen*	Delft, The Netherlands
III.2		2003 – 2007	*William E. Featherstone*	Perth, Australia
III.3		2007 – 2015	*Roland Klees*	Delft, The Netherlands
III:4		2015 – 2023	*Jürgen Kusche*	Bonn, Germany

Table 7 Editors of the International Association of Geodesy Symposia Series

No	*Period*	*Name of Editor*	*Residence*	*Name of Assistant Editor*	*Residence*
1	1991-1995	*Wolfgang Torge*	Hannover, Germany		
2	1995-1999	*Klaus-Peter Schwarz*	Calgary, Canada		
3	1999-2003	*Fernandó Sansó*	Milan, Italy		
4	2003-2007	*Gerhard Beutler*	Bern, Switzerland		
5	2007-2011	*Michael G. Sideris*	Calgary, Canada		
6	2011-2015	*Chris Rizos*	Sydney, Australia	Pascal Willis	Paris, France
7	2015-2023	*Jeff Freymueller*	Fairbanks, USA	Laura Sánchez	Munich, Germany

Table 8 Editors of The Geodesist's Handbook

No	*Year*	*Editor*	*Residence*
1	1980	*Ivan I. Mueller*	Columbus, USA
2	1984	*Carl Christian Tscherning*	Copenhagen, Denmark
3	1988	*Carl Christian Tscherning*	Copenhagen, Denmark
4	1992	*Carl Christian Tscherning*	Copenhagen, Denmark
5	1996	*Pascal Willis*	Paris, France
6	2000	*Ole B. Andersen*	Copenhagen, Denmark
7	2004	*Ole B. Andersen*	Copenhagen, Denmark
8	2008	*H. Drewes, H. Hornik / J. Ádám, Sz. Rózsa*	Munich, Germany / Budapest, Hungary
9	2012	*H. Drewes, H. Hornik / J. Ádám, Sz. Rózsa*	Munich, Germany / Budapest, Hungary
10	2016	*H. Drewes, F. Kuglitsch / J. Ádám, Sz. Rózsa*	Munich & Potsdam, Germany / Budapest, Hungary
11	2020	*M. Poutanen / Sz. Rózsa*	Masala, Finland / Budapest, Hungary

Table 9 Awardees of the IAG Levallois Medal

No	*Year*	*Name of Awardee*	*Residence*
1	1979	*Charles Whitten*	Washington, USA
2	1983	*Rudolf Sigl*	Munich, F.R.Germany
3	1987	*Arne Bjerhammar*	Stockholm, Sweden
4	1991	*Paul Melchior*	Brussels, Belgium
5	1995	*Willem Baarda*	Delft, The Netherlands
6	1999	*Torben Krarup*	Copenhagen, Denmark
7	2003	*George Veis*	Athens, Greece
8	2007	*Carl C. Tscherning*	Copenhagen, Denmark
9	2011	*Ruth E. Neilan*	Pasadena, USA
10	2015	*Reiner Rummel*	Munich, Germany
11	2019	*Christoph Reigber*	Potsdam, Germany

Table 10 Awardees of the IAG Guy Bomford Prize

No	*Year*	*Name of Awardee*	*Residence*
1	1975	*Erik Grafarend*	Munich, F.R.Germany
2	1979	*Fernandó Sansó*	Milan, Italy
3	1983	*John Wahr*	Boulder, USA
4	1987	*Peter J. Teunissen*	Delft, The Netherlands
5	1991	*Shuhei Okubo*	Tokyo, Japan
6	1995	*Thomas Herring*	Cambridge, USA
7	1999	*Véronique Dehant*	Brussels, Belgium
8	2003	*Ramon Hanssen*	Delft, The Netherlands
9	2007	*Masato Furuya*	Tokyo, Japan
10	2011	*Johannes Böhm*	Vienna, Austria
11	2015	*Yoshiyuki Tanaka*	Tokyo, Japan
12	2019	*Michal Šprlák*	Newcastle, Australia

Table 11 Winners of the IAG Young Authors Award

No	*Year*	*Author's Name*	*Country*	*Title of the Publication*
1	1993	*Hussein A. Abd-Elmotaal*	Egypt	Vening-Meinesz Moho depths: traditional, exact and approximated. *Manuscripta Geodaetica*, 18: 171-181
2	1994	*Jean-Pierre Barriot*	France	Line of sight operators in planetary geodesy. *Manuscr. Geod.*, 19: 269-283
3	1995	*Srinivas V. Bettadpur*	India	Hotine's geopotential formulation revisited. *Bull. Géod.* 69: 135-142.
4	1996	*Giovanna Sona*	Italy	Numerical problems in the computation of ellipsoidal harmonics. *J. of Geodesy,* 70: 117-126.
5	1998	*Cheinway Hwang*	Taiwan	Inverse Vening-Meinesz formula and deflection-geoid formula: applications to the predictions of gravity and geoid over the South China Sea. *J. of Geodesy*, 72: 304-312.
6	1999	*Peiliang Xu*	China	Biases and accuracy of, and an alternative to, discrete nonlinear filters. *J. of Geodesy*, 73: 35-46.
7	2000	*Christopher Kotsakis*	Canada	The multiresolution character of collocation. *J. of Geodesy*, 74: 275-290

Table 11 continued

No	*Year*	*Author's name*	*Country*	*Title of the Publication*
8	*2000*	*Rüdiger Lehmann*	Germany	Altimetry-gravimetry problems w. free vertical datum. *J.Geod* 74:327-334.
9	*2001*	*Susan Skone*	Canada	The impact of magnetic storms on GPS receiver performance. *J. of Geodesy*, 75: 457-468.
10	2003	*Michael Kern*	Germany	A study on the combination of satellite, airborne and terrestrial gravity data. *Journal of Geodesy,* 77: 217-225.
11	2004	*Shfaqat Abbas Khan*	Pakistan	Shallow water loading tides in Japan from superconducting gravity (with J.L. Hoyer). *Journal of Geodesy*, 78: 245-250.
12	2005	*Roland Pail*	Austria	A parametric study on the impact of satellite attitude errors on GOCE gravity field recovery. *Journal of Geodesy*, 79: 231-241.
13	2006	*Steffen Schön*	Germany	Uncertainty in GPS networks due to remaining systematic errors: the internal approach (with H. Kutterer). *Journal of Geodesy*, 80: 150-162.
14	2008	*Franziska Wild-Pfeiffer*	Germany	A comparison of different mass elements for use in gravity gradiometry. *Journal of Geodesy*, 82: 637-653.
15	2010	*Elizabeth Petri*	UK	A first look at the effects of ionospheric signal bending on a globally processed GPS network. *Journal of Geodesy*, 84: 491-499.
16	2011	*Thomas Artz*	Germany	Assessment of periodic sub-diurnal Earth rotation variations at tidal frequencies through VLBI normal equations. *J. of Geodesy*, 85, 565-584.
17	2012	*Manuela Seitz*	Germany	The 2008 DGFI realization of the ITRS: DTRF2008. *Journal of Geodesy*, 86: 1097-1123.
18	2013	*Krzysztof Sośnica*	Switzer-land	Impact of loading displacements on SLR-derived parameters and on the consistency between GNSS and SLR results. *J. of Geodesy*, 87: 751-769.
19	2014	*Alvaro Santamaría Gómez*	France	Long-term vertical land motion from double-differenced tide gauge and satellite altimetry data. *Journal of Geodesy*, 88: 207-222.
20	2015	*Xingxing Li*	Germany	Accuracy and reliability of multi-GNSS real-time precise positioning: GPS, GLONASS, BeiDou, and Galileo. *J. of Geodesy*, 89: 607-635.
21	2016	*Olga Didova*	Nether-lands	An approach for estimating time-variable rates from geodetic time series. *Journal of Geodesy,* 90: 1207–1221.
22	2017	*Minghui Xu*	China	The impacts of source structure on geodetic parameters demonstrated by the radio source 3C371. *Journal of Geodesy,* 91: 767-781.
23	2018	*Athina Peidou*	Canada	On the feasibility of using satellite gravity observations for detecting large-scale solid mass transfer events. *J. of Geodesy,* 92: 517–528.

Table 12 History of IAG Services

No	*Acronym*	*Name of the IAG Service (and Address of the Homepage)*	*Formation*
1	**ILS**	International Latitude Service (1962 renamed International Polar Motion Service, IPMS)	1899
2	**BIH**	Bureau International de l'Heure (1987 integrated into IERS)	1912
3	**PSMSL**	Permanent Service for Mean Sea Level / *https://www.psmsl.org/*	1933
4	**BGI**	Bureau Gravimetrique International / *http://bgi.omp.obs-mip.fr*	1951
5	**ICET**	International Centre for Earth Tides (2015 integrated into IGETS)	1956
6	**IPMS**	International Polar Motion Service (Successor of ILS, 1987 integrated into IERS)	1962
6	**IERS**	International Earth Rotation and Reference Systems Service / *https://www.iers.org*	1987
7	**ISG**	International Service for the Geoid / *http://www.isgeoid.polimi.it*	1991

Table 12 continued

No	*Acronym*	*Name of the IAG Service (and Address of the Homepage)*	*Formation*
8	**IGS**	International GNSS Service / *http://www.igs.org*	1994
9	**ILRS**	International Laser Ranging Service / *https://ilrs.cddis.eosdis.nasa.gov/*	1998
3	**IDEMS**	International Digital Elevation Models Service / *https://idems.maps.arcgis.com/home/index.html*	1999
11	**IVS**	International VLBI Service for Geodesy and Astrometry / *https://ivscc.gsfc.nasa.gov*	1999
4	**IDS**	International DORIS Service / *https://ids-doris.org/*	2003
2	**ICGEM**	International Centre for Global Earth Models / *http://icgem.gfz-potsdam.de/home*	2003
7	**IGFS**	International Gravity Field Service / *http://igfs.topo.auth.gr/*	2004
6	**IGETS**	International Geodynamics and Earth Tide Service / *http://igets.u-strasbg.fr/*	2015

Table 13 Fellows of the IAG

1991:
D.A. Adebekun, Nigeria
D.-E. Ajakaiye, USA
V. Ashkenazi, UK
W. Augath, Germany
T.F. Baker, UK
G. Balmino, France
L.W. Baran, Poland
G. Birardi, Italy
A. Bjerhammar, Sweden
D. Blitzkow, Brazil
Y. Bock, USA
G. Boedecker, Germany
J.D. Bossler, USA
C. Boucher, France
P. Brosche, Germany
F.K. Brunner, Austria
M. Burša, Czech Republic
J. Campbell, Germany
G. Carrera, Canada
M. Charfi, Tunisia
J. Y. Chen, China
B. H. Chovitz, USA
O. Coker, Nigeria
O. L. Colombo, USA
A. Comolet-Tirman, France
A.H. Cook, UK
P.A. Cross, UK
K. I. Daugherty, USA
P. de Jonge, USA
A. Dermanis, Greece
J.O. Dickey, USA
A.H. Dodson, UK
B.C. Douglas, USA
A. Drozyner, Poland
H. Dufour, France
D. Eckhardt, USA
O. Fadahunsi, Nigeria
F. Fajemirokun, Nigeria
M. Feissel-Vernier, France
I. Fejes, Hungary
I.K. Fischer, USA
R. Forsberg, Denmark
P. Forsyth, Canada
D. Fritsch, Germany
J. Gaignebet, France
E.M. Gaposchkin, USA
C. Gemael, Brazil
C.C. Goad, USA
E.W. Grafarend, Germany
E. Groten, Germany
E. Gubler, Switzerland
B. Guinot, France
B. Heck, Germany
G. Hein, Germany
H. Henneberg, Venezuela
S. Henriksen, USA
P. Holota, Czech Republic
L. Hora, Czech Republic
H.T. Hsu, China
J.R. Huddle, USA
C. Jekeli, USA
G. Jentzsch, Germany
I. Joó, Hungary
C.S. Joshi, India
H.-G. Kahle, Switzerland
H.P. Kahmen, Austria
J. Kakkuri, Finland
K. Kasahara, Japan
E. Kausel, Chile
H. Kautzleben, Germany
A.H.W. Kearsley, Australia
R.W. King, USA
A. Kiviniemi, Finland
R. Klees, The Netherlands
K.R. Koch, Germany
B. Kolaczek, Poland
K. Konan, Ivory Coast
J. Kovalevsky, France
Y. Kozai, Japan
J. Krynski, Poland
M. Kumar, USA
J.T. Kuo, USA
M.P.M. Lefebvre, France
D. Lelgemann, Germany
G.W. Lennon, Australia
G. Lensen, New Zealand
J-J. Levallois, France
E. Livieratos, Greece
M. Louis, France
G.R. Mader, USA
J. Makris, Germany
A. Mancini, USA
I. Marson, Italy
M. McNutt, USA
D.D. McCarthy, USA
W.G. Melbourne, USA
P. Melchior, Belgium
C. Morelli, Italy
H. Moritz, Austria
I.I. Mueller, USA
I. Nakagawa, Japan
A. Nobili, Italy
J.D. Obel, Kenya
M.Odlanicki-Poczobut, Poland
B.P. Pertsev, Russia
K. Poder, Denmark
C. Poitevin, Belgium
M.T. Prilepin, Russia
J. Rais, Indonesia
R.H. Rapp, USA
C. Reigber, Germany
A.R. Robbins, UK
R.S. Rostom, Kenya
R. Rummel, Germany
F. Sacerdote, Italy
F. Sansó, Italy
N.K. Saxena, USA
B. Schaffrin, USA
G. Schmitt, Germany
B.E. Schutz, USA
K.-P. Schwarz, Canada
G. Seeber, Germany
M.J. Sevilla, Spain
P.J. Shelus, USA
M.G. Sideris, Canada
L.E. Sjöberg, Sweden
R.A. Snay, USA
H. Sünkel, Austria
T. Tanaka, Japan
P. Teunissen, The Netherlands
W. Torge, Germany
C.C. Tscherning, Denmark
P. Vaníček, Canada
C. Veillet, France
P. Vyskočil, Czech Republic
A. Waalewijn, The Netherlands
J. Wahr, USA
D.E. Wells, Canada
W.M. Welsch, Germany
L.A. White, Australia
P. Wilson, Germany
P.L. Woodworth, UK
Y.Y. Yatskiv, Ukraine
K. Yokoyama, Japan
D.B. Zilkoski, USA
J.D. Zund, USA

1995:
J. Ádám, Hungary
R. Barzaghi, Italy
M. Becker, Germany
G. Beutler, Switzerland
W. Bosch, Germany
B.F. Chao, USA
H. Denker, Germany
J. Dow, Germany
G.K. Elgered, Sweden
B. Engen, Norway
A. Geiger, Switzerland
T. Kato, Japan
A. Kleusberg, Germany
J. Kouba, Canada
H. Landau, Germany
R.B. Langley, Canada
K. Linkwitz, Germany
S. Molodensky, Russia
R. Neilan, USA
C. Noll, USA
S. Okubo, Japan
P. Pâquet, Belgium
J.C. Ries, USA
J.M. Rüeger, Australia
E.J.O. Schrama, The Netherlands
C.-K. Shum, USA
T.A. Spoelstra, The Netherlands
S. Takemoto, Japan
C. Thomas, France
J.A. Weightman, UK
P. Willis, France
C. Wilson, USA
T. Yunck, USA

1999:
N. Andersen, Denmark
O. Andersen, Denmark
D. Arabelos, Greece
M.G. Arur, India
L. Ballani, Germany
G.B. Benciolini, Italy
M.G. Bevis, USA
G. Blewitt, UK
J.M. Bosworth, USA
A. Cazenave, France
T.A. Clark, USA
J. Degnan, USA
V. Dehant, Belgium
H. Drewes, Germany
B. Ducarme, Belgium
W. Featherstone, Australia
W. Freeden, Germany
T. Herring, USA
K.-H. Ilk, Germany
J. Johanssen, Sweden
P. Knudsen, Denmark
Z.-X. Li, China
J. Manning, Australia
N. Pavlis, USA
C. Rizos, Australia
C. Rocken, USA
I.N. Tziavos, Greece
M. Vermeer, Finland
M. Wei, Canada
D. Wolf, Germany
S. Zerbini, Italy

2003:
E.F. Arias, Argentina
J.-P. Barriot, France
P.A. Berry, UK
C.A. Brunini, Argentina
C. Bruyninx, Belgium
D. Gambis, France
G. Gendt, Germany
R.S. Gross, USA
W. Gurtner, Switzerland
S. Han, Australia
R. Hanssen, The Netherlands
B.G. Harsson, Norway
C. Hwang, Taiwan
W. Keller, Germany
S.C. Kenyon, USA
R. Kursinski, USA
H. Kutterer, Germany
R. Lehman, Germany
A. Marchenko, Ukraine
R. Scharroo, The Netherlands
W. Schlüter, Germany
T. Schöne, Germany
S. Skone, Canada
N. Sneeuw, Canada
M. Stewart, Australia
G. Strykowski, Denmark
C. Tiberius, The Netherlands
H. van der Marel, The Netherlands
N. Vandenberg, USA
P. Visser, The Netherlands
L. Vitushkin, France
J. Vondrak, Czech Republic
R. Weber, Austria
Y. Yuanxi, China

2007:
Z. Altamimi, France
R. Biancale, France
M. Craymer, Canada
D. Crossley, USA
R. Dietrich, Germany
X. Ding, Hong Kong
L.P.S. Fortes, Brazil
Y. Gao, Hong Kong
D. Grejner-Brzezinska, USA
K. Heki, Japan
L. Hothem, USA
J. Huang, China
J. Ihde, Germany
M. Kuhn, Australia
J. Kusche, The Netherlands
U. Marti, Switzerland
C. Merry, South Africa
A.W. Moore, USA
P. Novák, Czech Republic
M.C. Pacino, Argentina
M.R. Pearlman, USA
H.-P. Plag, USA
M. Poutanen, Finland
B. Richter, Germany
M. Rothacher, Germany
Sz. Rózsa, Hungary
M. Scheinert, Germany
H. Schuh, Austria
H.-P. Sun, China
J.A. Torres, Portugal
Gy. Tóth, Hungary
P. Tregoning, Australia
M. Verroneau, Canada
J. Wang, Australia
R. Wonnacott, South Africa
P. Xu, Japan
J. Yu, China
S.Y. Zhu, Germany

2011:
H. Abd-Elmotaal, Egypt
L. Alfonsi, Italy
D. Behrend, USA
S. Bettadpur, USA
S. Bisnath, Canada
A. Brzezinski, Poland
T. van Dam, Luxembourg
J. Davis, USA
Y. Feng, Australia
J. Freymueller, USA
Y. Fukuda, Japan
Th. Hobiger, Japan
H. Hornik, Germany
S. Jin, South Korea
M.O. Karslioglu, Turkey
Ch. Kotsakis, Greece
S. Lambert, France
F. Lemoine, USA
C. Ma, USA
Z. Malkin, Russia
S. Matsuzaka, Japan
Gy. Mentes, Hungary
A. Michlenz, Germany
M. Omura, Japan
R. Pail, Germany
J. Ray, USA
A. Reiterer, Germany
G. Retscher, Austria
L.J. Rickards, UK
D. Roman, USA
L. Sanchez, Germany
M. Santos, Canada
M. Schmidt, Germany
F. Seitz, Germany
L. Soudarin, France
G. Tavernier, France
S. Verhagen, The Netherlands
Y.M. Wang, USA
J. Wickert, Germany
H. Wilmes, Germany

2015:

D. Angermann, Germany
D. Avalos, Mexico
F. Barthelmes, Germany
O. Baur, Austria
J. Boehm, Austria
J. Bogusz, Poland
S. Bonvalot, France
C. Braitenberg, Italy
J. Chen, USA
R. Cunderlik, Slovakia
X. Deng, Australia
J. Dawson, Australia
A. Eicker, Germany
J. Ferrandiz, Spain
Ch. Gerlach, Germany
M. Hashimoto, Japan
A. Jäggi, Switzerland
G. Johnston, Australia
A. Kealy, Australia
Sh. Abbas Khan, Denmark
M. King, Australia
W. Kosek, Poland
K. Mikula, Slovakia
H. Ozener, Turkey
S. Pagiatakis, Canada
V. Palinkas, Czech Republic
M. Reguzzoni, Italy
S. Rosat, France
M. Thomas, Germany
M. Weigelt, Germany
B. Wouters, UK/USA
Li Zhenhong, UK

2019:

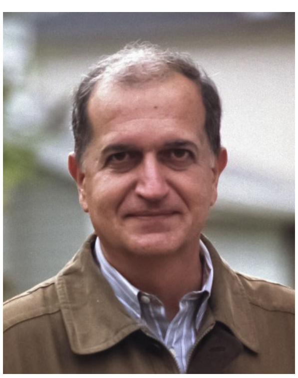
J. Agren, Sweden
M. Alizadeh, Iran
S. Bergstrand, Sweden
G. Bianco, Italy
S. Claessens, Australia
X. Collilieux, France
L. Combrinck, South Africa
M. Crespi, Italy
J. Dousa, Czech Republic
A. El-Mowafy, Australia
Ch. Eschmann, Germany
F. Flechtner, Germany
J J. Flury, Germany
J. Geng, China
V. Gikas, Greece
R. Heinkelmann, Germany
Ch. Hirt, Germany
M. Hoque, Germany
M. Horwath, Germany
C. Huang, China
U. Hugentobler, Germany
M. Kalantari, Australia
A. Kenyeres, Hungary
A. Khodabandeh, Australia
F. Kuglitsch, Germany
J. LaBrecque, USA
B. Luzum, USA
D. MacMillan, USA
W. Martinez, USA
J. Müller Germany
F. Nievinski, Brazil
A. Nothnagel, Germany
R. Pacione, Italy
J.-A. Paffenholz, Germany
E. Pavlis, USA
U. Schreiber, Germany
M. Seitz, Germany
J. Skaloud, Switzerland
K. Sosnica, Poland)
R. Stanaway, Australia
D. Thaller, Germany
L.-C. Tsai, China-Taipei
D. Tsoulis, Greece
G. Vergos, Greece
P. Wielgosz, Poland
H. Wziontek, Germany
K. Zhang, Australia
X. Zhang, China

Past Officers of the International Association of Geodesy (2007 – 2019)

Compiled by **Hermann Drewes**
IAG Honorary Secretary General
Technical University Munich, Arcisstr. 21, 80333 München, Germany
h.drewes@tum.de

This Chapter continues the series of articles "History of the International Association of Geodesy". In Geodesist's Handbook 2008 article "Past officers of the International Association of Geodesy (1991-2007)", Bulletin Géodésique (82) 675-679, 2008, *Carl Christian Tscherning* summarises the CVs of the Presidents and Secretaries General during this period. He refers there to a publication of his Secretary General (pre-)predecessor, *Michel Louis*, who wrote a similar article in 1992, and refers on his part to an article on the History of IAG, written by the previous Secretary General *J.-J. Levallois* in 1980.

Michael Sideris
President 2007 – 2011



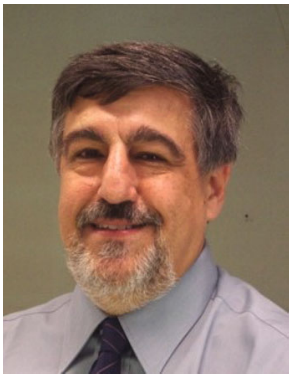
Michael George Sideris was born on August 16, 1958, in Pireaus, Greece. He received his Dipl.-Ing. (honours) degree in surveying engineering from the National Technical University of Athens, Greece, in 1981. In 1982, he moved to Canada to continue his studies in geodesy at the Department of Surveying of the University of Calgary (UofC). He obtained his MSc degree in 1984 and his PhD degree in 1988. After he graduated, he was offered a tenured faculty position at UofC, and he became full professor of geodesy. He has also served in major administrative positions, as Associate Dean Research in the Faculty of Engineering (1999-2005) and Associate Dean in the Faculty of Graduate Studies (2003-2011).

His research work focuses on physical geodesy, such as gravity field approximation, precise geoid determination, vertical datums, satellite altimetry, terrestrial, satellite and airborne gravimetry and gradiometry, geodetic applications of wavelets and spectral methods, and geodetic methods for hazards monitoring and resource exploration. His pioneering research on efficient spectral methods for precise geoid determination and geodetic boundary value problem (Stokes and Molodensky) solutions earned him an international reputation, and the FFT-based software he developed has been commercialized by UofC's technology commercialization office and is being used internationally by universities, national agencies and geophysical industry.

For his contributions to geodesy, he has been awarded an Alexander von Humboldt International Research Fellowship (hosted at the University of Stuttgart, Germany, in 1998) and a Dr. honoris causa honorary doctorate degree (2004) by the University of Architecture, Civil Engineering and Geodesy, in Sofia, Bulgaria.

Michael Sideris was first involved with the IAG in 1984 during the International Summer School on Local Gravity Field Approximation in Beijing, China. Since then, he has served the IAG in many leadership positions, including as Secretary (1995-1999) and President (1999-2003) of IAG's Section III "Determination of the Gravity Field", IAG Vice President (2003-2007) and IAG President (2007-2011). He has also organized numerous sessions at IAG, IUGG, EGU and AGU assemblies. He has taught at nine IAG Schools on the Determination and Use of the Geoid, as well as at the First IAG School on Reference Frames in 2010. At the IUGG General Assembly 2011, he was elected Vice President of the IUGG, and at the General Assembly 2015 President of the IUGG.

Chris Rizos
President 2011 – 2015



Chris Rizos was born on October 16, 1952. He received his BSurv in 1975 and his PhD in 1980 from the School of Surveying, University of New South Wales (UNSW), Sydney, Australia. In 1987, he joined the academic staff of UNSW, and was promoted to Professor in 2001. Chris was Head of the UNSW School of Surveying and Geospatial Engineering (formerly School of Surveying) from 2004 until 2013 when it merged with the School of Civil and Environmental Engineering. Chris has been researching the technology and high precision applications of GPS since 1985, and has established the Satellite Navigation and Positioning Lab at UNSW in the early 1990s - Australia's premier academic R&D group for GNSS and wireless positioning technology and applications.

The principal research interests of *Chris Rizos* include the carrier phase-based kinematic GPS/GNSS positioning on short, medium and long baselines, the development of GPS/GNSS-based deformation monitoring systems, and low-cost GPS systems for survey applications and building monitoring. He conducted studies on a modern geodetic datum for upgrade of the Australian Geodetic Datum using GNSS and ITRF global products and innovative geodetic techniques. Other topics are the integration of GNSS with Interferometric SAR techniques, the development of multi-functional CORS networks and "smart" GNSS receivers. He studied new positioning technologies like indoor positioning, pseudolites, Locata, WiFi and mobilephone positioning, GNSS+INS (and other sensors) integration.

Chris Rizos received the following honours and awards:

- University Medal, UNSW, 1975;
- Commonwealth Postgraduate Scholarship, 1975-78;
- Fulbright Fellowship (Postgraduate Category), 1977-78;
- Rothmans Fellowship, 1979;
- Alexander von Humboldt Fellowship, 1981-83, 1991;
- Fellow of the Australian Institute of Navigation, 1999;
- Fellow of the International Association of Geodesy, 1999;
- Fellow of the U.S. Institute of Navigation, 2012;
- Honorary Professor, Wuhan University, China, 2006.

The first IAG office of *Chris Rizos* was the membership in the joint IAG/IHO Advisory Board on the Law of the Sea (ABLOS) from 1995-2011, whose Chair he became in 2009. In the same year, he joined the Steering Committee of the Asia-Pacific Reference Frame (APREF). In 2004, he was appointed member of the Governing Board of the International GNSS Service (IGS), and in 2006 member of the IGS Executive Committee. After the election as IAG Vice President in 2007, he was elected IAG President in 2011. At the IUGG General Assembly 2015, the IUGG Council elected him Member of the IUGG Bureau, and in 2019 President Elect of the IUGG.

Harald Schuh
President 2015 – 2019

Harald Schuh was born on February 27, 1956, in Heidelberg, Germany. He received his Dipl.-Ing. (Geodesy) in 1979 and his Dr.-Ing. in 1986 from the University Bonn. He worked there in the scientific staff of the Geodetic Institute from 1980 to 1986 and became a Junior Professor in 1987. From 1989 to 1995, he was a scientist at the German Aerospace Center (DLR) and changed then to the German Geodetic Research Institute (DGFI). In 2000, he followed a call as a Professor at the University of Technology, Vienna, Austria, and 2012 as a Professor at the Technical University Berlin, Germany, combined with the Head of the Section Geodesy of the GFZ German Research Centre.

Harald Schuh became internationally known by his research in Very Long Baseline Interferometry (VLBI). The research field includes parts of astrophysics and geodynamics, time series analysis, and monitoring of Earth rotation. His responsibilities in IAG started in 2003 as a representative of the Services in the IAG Executive Committee and the IAG representative to the International IVS Service (VLBI). In the same year, he became member of the Directing Board of the International Center for Earth Tides (ICET). In 2007, he was appointed Chair of the IVS Directing Board and the Sub-commission Interaction of Celestial and Terrestrial Reference Frames. He was elected Vice President of the IAG in 2011 and President in 2015.

From 2007 to 2012, *Harald Schuh* was the President of Commission 19 "Rotation of the Earth" of the International Astronomic Union (IAU), and acted in its Organizing Committee from 2006 to 2015.

Harald Schuh received the following major awards:

- Descartes Prize of the European Commission for the Project "Non-rigid Earth nutation model – Pinpoint positioning in a wobbly world" (team prize);

- Fellow of the International Association of Geodesy, 2007;
- Doctor honoris causa (Dr.h.c.), University for Architecture, Civil Engineering and Geodesy, Sofia, Bulgaria, 2009;
- Vening Meinesz Medal of the European Union, 2011;
- Adjunct Professor of the University Tehran, Iran, 2016;
- Member of the German National Academy of Science and Engineering (acatech), 2017.

Hermann Drewes
Secretary General 2007 – 2019

Hermann Drewes was born on April 26, 1944, in Lower Saxony, Germany. He received his Dipl.-Ing. in 1970 and his Dr.-Ing. in 1975 from the Technical University Hannover, Germany. Since 1970, he worked there in the Institute for Theoretical Geodesy as scientific assistant, and since 1976 as chief engineer. From 1977 to 1979, he was granted a leave as professor at the University of Zulia, Maracaibo, Venezuela. After his return, he changed as a senior scientist to the German Geodetic Research Institute (DGFI), where he became Director in 1994. In the same year he was awarded Honorary Professor at the Technical University Munich, Germany.

The key research fields of Hermann Drewes include gravimetry and geoid determination (since 1970), geodetic geodynamics (since 1979), and reference systems and frames (since 1994). Major international positions are:

- IAG Representative to the South American Reference Frame (SIRGAS) since 1994;
- President of the IAG/COSPAR Commission on Space Techniques for Geodesy and Geodynamics, 1999-2003;
- Member of the Bureau of the International Lithosphere Project (ILP), 2001-2008;
- Chair of the International Terrestrial Reference Frame (ITRF) Combination Centre at DGFI, 2001-2010;
- President of IAG Commission 1 “Reference Frames”, 2003-2007;
- IUGG Representative to the UN Cartographic Bureau, 2003-2007;
- IUGG Representative to the Pan-American Institute for Geography and History (PAIGH), 2003-2011;
- Secretary of IAG's Global Geodetic Observing System (GGOS), 2003-2005;
- IAG Secretary General, 2007-2019;
- IUGG Representative to the United Nations Geospatial Information Section, 2015 -2019.

Hermann Drewes received the following major awards:

- Fellow of the International Association of Geodesy (IAG), 1999;
- Cavaleiro do Ordem do Mérito Cartográfico, Brazilian Society of Cartography, Photogrammetry and Remote Sensing, 2005;
- Cross of the Order of Merit of the Federal Republic of Germany, 2007;
- Huesped de Honor Extraordinario, National University of La Plata, Argentina, 2010;
- Fellow of the International Union of Geodesy and Geophysics (IUGG), 2019.

IAG Statutes adopted by the IAG Council at the XXVII IUGG General Assembly in Montreal, Canada, 2019

1. Definition of Terms

(a) Geodesy is the discipline that deals with the measurement and representation (geometry, physics, and temporal variations) of the Earth and other celestial bodies.

(b) IUGG is an acronym for the International Union of Geodesy and Geophysics.

(c) IAG or Association is an acronym for the International Association of Geodesy.

(d) Adhering Body and Council have the same meaning as in the Statutes of the IUGG.

(e) IAG General Assembly refers to an assembly for scientific and/or administrative purposes of:
   (i) scientists from geodesy and other Earth science disciplines;
   (ii) the Council Delegates (or Alternative Delegates) appointed by the Adhering Bodies; and
   (iii) individual members as defined by Statute 6(b).

(f) IAG Scientific Assembly means an assembly for primarily scientific purposes and therefore it does not normally require the presence of the delegates appointed by the Adhering Bodies.

(g) Council Delegate means the person appointed by the Adhering Body to be a member of the Council for one period (see 1(h)). Adhering Bodies may appoint an Alternative Delegate to an IAG Council meeting if the Council Delegate cannot attend the meeting.

(h) Period means the interval of time between the closures of two successive IAG General Assemblies.

2. International Association of Geodesy

(a) The International Association of Geodesy (IAG):
   (i) is a constituent Association of the IUGG; and
   (ii) is subject to the Statutes and Bylaws of the IUGG

(b) In the event of the dissolution of the IAG, its assets shall be ceded to the IUGG.

3. Mission

The Mission of the Association is the advancement of geodesy. The IAG implements its mission by furthering geodetic theory through research and teaching, by collecting, analyzing, modelling and interpreting observational data, by stimulating technological development and by providing a consistent representation of the figure, rotation, and gravity field of the Earth and planets, and their temporal variations.

4. Objectives

The IAG shall pursue the following objectives to achieve its mission:

(a) Study, at the highest possible level of accuracy, all geodetic problems related to Earth observation and global change, including:
   (i) Definition, establishment, and maintenance of global and regional reference systems for interdisciplinary use.
   (ii) Rotation of the Earth and planets.
   (iii) Positioning and deformation.
   (iv) Gravity field.
   (v) Ocean, ice and sea level.
   (vi) Atmosphere and hydrosphere.
   vii) Time and frequency transfer.

(b) Support the maintenance of geodetic reference systems and frames for continuous, long-term observations and archival of results.

(c) Provide observational and processed data, standards, methodologies, and models in a form that ensures the broadest possible range of research and application.

(d) Stimulate development and take advantage of emerging space and other technologies to increase the resolution and accuracy of geodetic data and products in order to advance geodetic and interdisciplinary research.

(e) Initiate, coordinate, and promote international cooperation and knowledge exchange through symposia, workshops, summer schools, training courses, publications, and other means of communication.

(f) Foster the development of geodetic activities and infrastructure in all regions of the world, taking into consideration the specific situation of developing countries.

(g) Collaborate with the international science and engineering community in supporting the application of geodetic theory and techniques and the interpretation of results.

(h) Cooperate with national and international agencies in establishing research goals, missions, and projects.

5. Structure and Administration

(a) The Association's structure shall comprise a small number of components: Commissions, Inter-commission Committees (ICC) (such as the ICC on Theory (ICCT)), the Services, the Global Geodetic Observing System (GGOS), and the Communication and Outreach Branch (COB).

(b) Subcomponents, such as IAG Projects, Sub-commissions, Commission Projects, and Study and Working Groups, may be established as provided for in the Bylaws.

(c) The administration of the IAG is carried out by the IAG General Assembly, the IAG Council, the IAG Bureau and the IAG Executive Committee. The COB is the office responsible for the promotional activities of the IAG and the communication with its members.

6. Membership

The membership of the IAG shall comprise:

(a) Adhering Bodies; and
(b) Individual members in accordance with the Bylaws.

7. IAG Council

(a) The IAG Council is responsible for governance, strategic policy and direction.

(b) The membership of the IAG Council consists of Delegates appointed by the Adhering Bodies.

(c) Each Adhering Body may appoint one Delegate subject to the conditions in (d) and (e) below.

(d) A Delegate may only represent one Adhering Body.

(e) The IAG President, Vice President and Secretary General may not serve as Delegates.

8. IAG Bureau

(a) The Bureau of the Association consists of the IAG President, the Vice President and the Secretary General.

(b) The duties of the IAG Bureau shall be to administer the affairs of the Association in accordance with these Statutes and Bylaws and with the decisions of the IAG Council and the IAG Executive Committee.

9. IAG President

(a) The IAG President shall be elected by the IAG Council.

(b) The IAG President shall provide general leadership for the Association.

(c) The IAG President presides over the meetings of the IAG General Assembly, the IAG Scientific Assembly, the IAG Council, the IAG Executive Committee, and the IAG Bureau. In the IAG Council meetings the President has no vote, except in the case of a tie as provided in 14(g).

(d) The IAG President, on completion of their term of office of one period, shall serve for the next period in the position of Immediate Past President.

10. IAG Vice President

(a) The IAG Vice President shall be elected by the IAG Council.

(b) The IAG Vice President shall perform such tasks as may be assigned by the IAG President, the IAG Executive Committee or the IAG Council.

(c) The IAG Vice President assumes the functions, duties and powers of the President when the latter is absent or otherwise unable to assume office.

11. IAG Secretary General

(a) The IAG Secretary General shall be elected by the IAG Council.

(b) The IAG Secretary General shall serve as secretary of the IAG General Assembly, the IAG Scientific Assembly, the IAG Council, the IAG Executive Committee, and the IAG Bureau and arrange for meetings of these bodies in accordance with the Bylaws.

(c) The IAG Secretary General, on completion of their term of office, shall serve for the next period in the position of Immediate Past Secretary General.

12. IAG Executive Committee

(a) The IAG Executive Committee shall consist of the following voting members: each member of the IAG Bureau, the immediate Past President, the immediate Past Secretary General, the Presidents of the Commissions, the President of the ICCT, the President of GGOS, the President of the COB, the three representatives of the Services, and two Members-at-Large.

(b) Presidents of the Inter-commission Committees other than the ICCT, Chairs of the IAG Projects, and the Assistant Secretaries shall attend any meeting of the IAG Executive Committee, with voice but without vote. The Past Presidents and past Secretaries General may attend any meeting of the IAG Executive Committee, with voice but without vote (except for the immediate Past President and the immediate Past Secretary General, who do have a vote in accordance with Statute 12(a) for one 4-year period).

(c) The election of IAG Executive Committee members shall be in accordance with the Bylaws.

(d) The responsibilities of the IAG Executive Committee shall be to further the objectives of the Association through effective coordination and through the formulation of general policies.

(e) Decisions of the Executive Committee shall be taken by a simple majority. If a tie should occur in an Executive Committee vote, the IAG President shall cast the decisive vote.

13. Council Meetings

(a) The IAG Council shall meet at the time of an IAG General Assembly.

(b) The IAG Council may hold extraordinary meetings, either in person or electronically, at times other than an IAG General Assembly. Such meetings must be proposed by the IAG Executive Committee

(c) The members of the IAG Executive Committee may attend meetings of the IAG Council, with voice but without vote, except for those who are also Delegates.

14. Voting in the Council

Voting in the IAG Council shall follow the following rules:

(a) An Adhering Body which is not represented at an IAG Council meeting may vote by correspondence on any specific question, provided that the matter has been clearly defined on the final agenda distributed in advance, and that the discussion thereon has not produced any significant new considerations or change in its substance, and that the said vote has been received by the IAG President prior to the voting. In such a case the vote will be cast in accordance with 14(d)).

(b) Quorum in IAG Council meetings is achieved when the number of Council Delegates (or Alternative Delegates) in attendance is at least one third of the delegates from countries eligible to vote.

(c) On questions not involving matters of finance, each delegate from an Adhering Body, with its IUGG subscriptions paid up to the end of the calendar year preceding the voting, shall have one vote.

(d) On questions involving finance, each delegate from an Adhering Body, which has paid its IUGG subscriptions up to the end of the calendar year preceding the voting, shall have the right to vote. The number of votes allotted to each delegate of an Adhering Body shall then be in accordance with its category of membership, as defined by the IUGG.

(e) Prior to any vote in an IAG Council meeting, the IAG President shall decide whether or not the matter under consideration is financial in character and whether the procedure of voting by correspondence applies.

(f) The IAG Council may also deliberate and decide matters at other times by correspondence and/or email ballot, provided that the issues have been communicated to IAG Council members at least one month in advance of the voting date.

(g) Decisions of the IAG Council shall be taken by a simple majority, except as otherwise specified in these Statutes. If a tie should occur in an IAG Council vote, the IAG President shall cast the decisive vote. This procedure also applies if the vote is taken by email ballot. Simple and two-thirds majorities are determined by the proportion of affirmative votes to the sum of all votes (affirmative, negative and abstention). Blank and invalid ballots and votes not cast by delegates present are counted as abstentions.

(h) Elections for all for members of the IAG Executive Committee shall be by electronic ballot. For each post, the winner must receive an outright majority (number of votes being greater than the total combined votes of the other candidates). If there are three or more candidates for a position and no candidate has an outright majority after the first voting round, then the top two ranked candidates will be retained and a second round of votes conducted to elect the winner. Ties will be broken by a coin toss, drawing of lots, or equivalent random selection.

(i) Except as otherwise provided in the Statutes or Bylaws, meetings of the IAG Council, as well as those of other IAG administrative bodies, shall be conducted according to the edition of Robert's Rules of Order currently recommended by the IUGG.

15. Decisions of the Council

(a) Decisions of the IAG Council shall be reported to the individual membership in a meeting at the IAG General Assembly.

(b) If the majority of those present at this meeting disagrees with the decisions of the IAG Council, the IAG Council shall reconsider the question, and make a decision, which shall be final.

16. Changes to Statutes and Bylaws

Changes in the Statutes and Bylaws shall be made as follows:

(a) If deemed necessary, the Association may review the Statutes and Bylaws in each period, to ensure an up-to-date structure of its scientific and administrative organization. A Review Committee, known as the Cassinis Committee, will be appointed by the IAG Executive Committee to achieve this goal. Proposals for a substantive change of any article of these Statutes and Bylaws must reach the Secretary General at least two months before the announced date of the IAG Council meeting at which it is to be considered. The Secretary General shall notify all Adhering Bodies of any proposed changes at least one month before the announced date of the IAG Council meeting.

(b) The Statutes may not be modified except a two-thirds majority of votes cast at an IAG Council meeting, and changes shall come into force at the close of that meeting.

(c) The IAG Council shall have the power to adopt Bylaws within the framework of the Statutes.

(d) The Bylaws may be modified by a simple majority of votes cast at an IAG Council meeting, and changes shall come into force at the close of the meeting.

IAG Bylaws adopted by the IAG Council at the XXVII IUGG General Assembly in Montreal, Canada, 2019

1. Definition of Terms

(a) **Association component** or **components** refers to the Commissions, the Inter-commission Committee on Theory (ICCT), other Inter-commission Committees as they may be established, IAG Projects, the Services, the Global Geodetic Observing System (GGOS), and the Communication and Outreach Branch (COB).

(b) **Commissions** represent major fields of activity in accordance with the IAG Statutes.

(c) **Services** collect and analyze observations to generate products relevant to geodesy and other sciences and applications.

(d) The Global Geodetic Observing System (GGOS) works with the IAG components in advancing our understanding of the dynamic Earth system by quantifying our planet's changes in space and time.

(e) **Association subcomponent** or **subcomponents** are long-term or short-term structures created by the IAG or one or more of its components.

(f) **Long-term subcomponents** comprise IAG Projects (broad in scope and of high interest for the entire field of geodesy), Sub-commissions and Commission Projects which are expected to operate for several periods.

(g) **Short-term subcomponents** refer to Study Groups and Working Groups which are established for a maximum term of one period.

(h) **Steering Committee** means a group of elected or appointed IAG officers who oversee the work of Commissions, Inter-commission Committees (see 17), IAG Projects (see 16), and the Communication and Outreach Branch (see 18).

(i) **Period** means the interval of time between the closures of two successive IAG General Assemblies.

2. Responsibilities of Association Components

(a) The scientific work of the IAG is performed by Commissions, Inter-commission Committees, IAG Projects, Services and the GGOS.

(b) The responsibilities of the IAG Components are determined by the IAG Council on the recommendation of the IAG Executive Committee.

(c) Components are expected to interact with each other where their activities are inter-related.

(d) Each Component may set up subcomponents and is responsible for the activities of those subcomponents.

3. General Responsibilities of Component Presidents or Chairs, and Steering Committees

(a) Each Component shall have a President or Chair who will lead a Steering Committee.

(b) The Component President or Chair is responsible for the scientific development within the Component's field of interest. The Component's President or Chair shall:
- (i) coordinate the work of the subcomponents;
- (ii) keep the officers of the Component as well as the IAG Bureau and IAG Executive Committee informed of the Component's activities on an annual basis;

   (iii) collect reports of the subcomponents two months before each IAG General and Scientific Assembly for publication in the "Travaux de l'Association Internationale de Géodésie";
   (iv) receive suggestions for new subcomponents, and suggestions for continuation of existing ones; and
   (v) recommend changes to subcomponents to the IAG Executive Committee for approval.

(c) The Component's Steering Committee is expected to meet at least once per year and at least once during each IAG General Assembly.

(d) The Component's Steering Committee shall review at one of its meetings (usually the IAG General Assembly, or the IAG Scientific Assembly):
   (i) the activities of the subcomponents over the past period;
   (ii) the structure of the subcomponents; and
   (iii) the programs for the forthcoming period for those subcomponents that will be recommended for continuation.

(e) The Component's Steering Committee shall inform the Secretary General about all relevant issues.

(f) The Component's Steering Committee may organize scientific and organizational meetings and workshops provided that they are readily distinguished as being of a more limited scope than IAG Scientific Symposia or IAG Sponsored Symposia as described in Bylaws 28 and 29.

4. Commission Responsibilities

Commissions shall promote the advancement of science, technology and international cooperation in their field. They establish the necessary links with sister disciplines and with the relevant Services. Commissions shall represent the Association in all scientific domains related to their field of geodesy.

5. Commission Steering Committee

(a) The Commission Steering Committee shall be set up at each IAG General Assembly, following the election of the Association officers.

(b) The Steering Committee shall have the following voting members:
   (i) Commission President.
   (ii) Commission Vice President.
   (iii) Chairs of the Sub-commissions and Commission Projects.
   (iv) Up to three representatives of the Services relevant to the work of the Commission.
   (v) Up to two Members-at-Large to balance geographical and member country representation.

6. Appointment of Commission Officers

(a) The Commission President shall be elected by the IAG Council for one period without reappointment, except where exceptional circumstances justify reappointment.

(b) The Commission Vice President shall be appointed by the IAG Executive Committee for one period without reappointment, except where exceptional circumstances justify reappointment.

(c) Chairs of the Sub-commissions and Commission Projects shall be nominated by the Commission President and Vice President within two months following the General Assembly.

(d) The representatives of the Services shall be appointed by the Commission President and Vice President upon proposal of the Services.

(e) The Members-at-Large shall be nominated by the Commission President and Vice President within two months following the IAG General Assembly.

(f) The appointments of Members-at-Large and Chairs of Sub-commissions and Commission Projects take effect on approval of the nominations by the IAG Executive Committee.

7. Tasks of Commission Steering Committee

The Commission Steering Committee is subject to the general responsibilities of component Steering Committees in Bylaw 3(c), 3(d), 3(e), and 3(f). In particular, its tasks are to:

(a) Review the Commission's field of interests and objectives.

(b) Liaise with the other IAG Commissions, the Inter-commission Committees, and with similar organizations outside the IAG, as appropriate.

(c) Foster active participation of early career geodesists and geodesists from under-represented countries.

(d) Coordinate and review the work of its components and report at the time of the Scientific Assembly to the IAG

Executive Committee on the progress and performance of the components.

(e) Encourage and organize Commission and interdisciplinary symposia and/or sessions at major geodesy related international meetings.

(f) Maintain a Commission website and email service.

(g) As requested, nominate editors for the Journal of Geodesy.

8. Current Commissions

On the approval of these Bylaws, there shall be four Commissions with areas of scientific responsibility as outlined below:

(1) Commission 1: Reference Frames

(a) Establishment, maintenance, improvement of the geodetic reference frames.
(b) Advanced terrestrial and space geodetic techniques for the above purposes.
(c) International collaboration for the definition and deployment of networks of terrestrially-based space geodetic observatories.
(d) Theory and coordination of astrometric observation for reference frame purposes.
(e) Collaboration with space geodesy/reference frame related international services, agencies and organizations.

(2) Commission 2: Gravity Field

(a) Terrestrial, marine, and airborne gravimetry.
(b) Satellite gravity and altimetry observations.
(c) Gravity field modelling.
(d) Time-variable gravity field.
(e) Geoid determination and height systems.
(f) Satellite orbit modelling and determination.

(3) Commission 3: Earth Rotation and Geodynamics

(a) Earth orientation (Earth rotation, polar motion, nutation and precession).
(b) Earth tides.
(c) Tectonics and crustal deformation.
(d) Sea surface topography and sea level changes.
(e) Planetary and lunar dynamics.
(f) Effects of the Earth's fluid layers (e.g., post glacial rebound, loading).

(4) Commission 4: Positioning and Applications

(a) Terrestrial and satellite-based positioning systems development, including sensor and information fusion.
(b) Navigation and guidance of platforms.
(c) Interferometric laser and radar applications.
(d) Applications of geodetic positioning using geodetic networks, including monitoring of deformations.
(e) Applications of geodesy to engineering.
(f) Atmospheric investigations using space geodetic techniques.

9. Commission Subcomponents and Joint Subcomponents

(a) Commission subcomponents are Sub-commissions, Commission Projects, Study Groups, and Working Groups, which all belong to one Commission.

(b) If more than one component is involved in a subcomponent, the term “joint subcomponent” will be used, e.g. Joint Sub-commission, Joint Commission Project, Joint Study Group, Joint Working Group.

10. Sub-commissions and Joint Sub-commissions

(a) A Sub-commission may be set up for topics where the Commission plays a leading or coordinating role.

(b) Where a topic relates to the scientific responsibilities of more than one IAG component, a Joint Sub-commission shall be established under the lead of one Commission.

(c) A Sub-commission is expected to be established for several periods.

(d) Sub-commissions are established and terminated by the IAG Executive Committee upon recommendation from the Commission President.

(e) A proposal to the IAG Executive Committee for a Joint Sub-commission requires the recommendation of the Presidents of all contributing components.

11. Commission Projects and Joint Projects

(a) A Commission Project may be established when a new scientific method or a new technique is being developed, or when it seems appropriate to apply an existing technique to a specific geographic area where international collaboration is required.

(b) Where a topic for a Commission Project relates to the scientific responsibilities of more than one Commission, or a Commission and a Service, a Joint Commission Project shall be established under the lead of one Commission.

(c) A Commission Project is established for one period and may be extended for another period subject to a positive review.

(d) Commission Projects are established, extended and terminated by the IAG Executive Committee upon recommendation from the Commission President.

(e) A proposal to the IAG Executive Committee for a Joint Commission Project requires the recommendation of the Presidents of all contributing components.

12. Study Groups, Working Groups, Joint Study Groups and Joint Working Groups

(a) A Study Group or Working Group may be established at any time to address clearly defined well-focused scientific topics of limited scope within the field of the Component. A Study Group is dealing with more theoretical issues and a Working Group with more practical realizations.

(b) Where a topic for a Study Group or Working Group relates to the scientific responsibilities of more than one Component, a Joint Study Group or a Joint Working Group shall be established.

(c) A Study Group or Working Group is established for a maximum of one period.

(d) Study Groups and Working Groups, including the position of the group chair, are established and terminated by the IAG Executive Committee upon recommendation of the Component President.

(e) A proposal to the IAG Executive Committee for a Joint Study Group or Joint Working Group requires the recommendation of the Presidents of all contributing components.

(f) The Chair of a Study Group or Working Group is responsible for initiating and directing its work and appointing its members.

(g) Study Group and Working Group membership should be balanced so as to reflect international cooperation in its subject.

(h) A Study Group or Working Group may have at most 20 full members and an unlimited number of correspondent members.

(i) The Chair of each Study Group or Working Group shall issue a brief description of the work to be performed and a list of members, to be published in the Geodesist's Handbook after each IAG General Assembly.

(j) The Chair of each Study Group or Working Group shall report annually to its members and the Commission Steering Committee, on results achieved and outstanding problems.

13. IAG Services

(a) IAG Services (see Bylaw 14) generate products, using their own observations and/or observations of other services, relevant for geodesy and for other sciences and applications. Accuracy and robustness of products, quality control, timeliness, and state of the art quality are the essential aspects of the Services.

(b) Each IAG Service shall define its Terms of Reference as appropriate to accomplish its mission and shall submit the Terms of Reference to the IAG Executive Committee for approval.

(c) Each IAG Service shall have an IAG representative, appointed by the IAG Executive Committee, as a voting member of its directing or governing board.

(d) IAG Services are linked to at least one of the Commissions and may be also linked to other scientific organizations, such as the World Data System (WDS) or the International Astronomical Union (IAU).

(e) IAG Services should collaborate on a scientific basis with the Commissions, establish Joint Commission Projects and Joint Study Groups and help compile the Commissions' list of themes for Study Groups.

(f) Three representatives shall be elected in accordance with Bylaw 39 to the IAG Executive Committee to serve the interests of all Services.

(g) On any matter relating to the products of a Service, the Service shall represent the IAG.

14. Current IAG Services

There are twelve IAG Services at the time of adoption of these Bylaws:

(a) International Centre for Global Earth Models (ICGEM)

(b) International Digital Elevation Models Service (IDEMS)

(c) International DORIS Service (IDS)

(d) International Earth Rotation and Reference Systems Service (IERS)

(e) International Geodynamics and Earth Tides Service (IGETS)

(f) International GNSS Service (IGS)

(g) International Gravimetric Bureau (BGI)

(h) International Gravity Field Service (IGFS)

(i) International Laser Ranging Service (ILRS)

(j) International Service for the Geoid (ISG)

(k) International VLBI Service for Geodesy and Astrometry (IVS)

(l) Permanent Service for Mean Sea Level (PSMSL)

15. The Global Geodetic Observing System (GGOS)

(a) The GGOS is IAG's observing system to monitor the geodetic and the global geodynamic properties of the Earth as a system.

(b) The **Global Geodetic Observing System (GGOS)** works with the IAG Services to facilitate the production of geodetic products (including the geometric reference frames and the gravity field models) that are fundamental to science and society. In addition GGOS undertakes activities directed at improving the geodetic infrastructure that underpins the geodetic products. Further, GGOS takes advice from the Commissions and the ICCT concerning new developments, and keeps the Commissions and ICCT informed of the work of GGOS.

(c) GGOS operates under its own Terms of Reference, defined by the GGOS Coordinating Board and approved by the IAG Executive Committee. The GGOS procedures for the nomination and election of its Officers are specified in its Terms of Reference.

(d) The GGOS President is elected by the IAG Executive Committee from a slate of nominations submitted by the GGOS Coordinating Board in consultation with the Executive Committee. The President is appointed for one period, which may be renewed once.

16. IAG Projects

(a) IAG Projects are flagship long-term projects of broad scope and of significant interest for the entire field of geodesy.

(b) The establishment of an IAG Project shall be carried out by a planning group appointed by the IAG Executive Committee.

(c) The Project Steering Committee shall have the following voting members:
- (i) The Project Chair appointed by the IAG Executive Committee.
- (ii) One member from each Commission appointed by each Commission's Steering Committee.
- (iii) Two Members-at-Large proposed by the members of the Project Steering Committee identified in clause (i) and (ii) above and approved by the IAG Executive Committee.
- (iv) Chairs of the IAG Project Working Groups (if any).
- (v) Representatives of other IAG components, as appropriate.

(d) IAG Project subcomponents are known as Working Groups.

17. Inter-commission Committees (ICCs)

(a) Inter-commission Committees shall be responsible for well-defined, important and permanent tasks involving all Commissions.

(b) Each ICC shall have a Steering Committee, which shall include the following members:
- (i) President appointed by the IAG Executive Committee.
- (ii) Vice President appointed by the IAG Executive Committee on the recommendation of the President.
- (iii) One representative appointed by each Commission.

(c) The Terms of Reference for each ICC shall be developed by a planning group appointed by the IAG Executive Committee, for approval by the Executive Committee.

(d) ICCs will be established for at least two periods and shall be reviewed by the IAG Executive Committee every eight years.

(e) The ICCs shall report to the IAG Executive Committee.

17.1 The Inter-commission Committee on Theory (ICCT)

The mission of the ICCT is to interact and collaborate with other IAG components, in particular the Commissions and GGOS, in order to further the objectives of ICCT:

(i) to be the international focal point of theoretical geodesy;
(ii) to encourage and initiate activities to further geodetic theory in all branches of geodesy; and
(iii) to monitor research developments in geodetic modelling.

18. Communication and Outreach Branch (COB)

(a) The function of the Communication and Outreach Branch (COB) is to provide the Association with communication, educational/public information and outreach links to the membership, to other scientific organizations and to the world as a whole.

(b) The responsibilities of the COB shall include the following:

(i) Promote the recognition and usefulness of geodesy in general and the IAG in particular.
(ii) Publications (such as newsletters) and social media platforms.
(iii) Membership development.
(iv) General information service and outreach.

(c) The COB shall also assist the IAG Secretary General in the following tasks as required:

(i) Maintenance of the IAG website.
(ii) Setting up Association schools.
(iii) Organizing meetings and conferences.

(d) The IAG Executive Committee establishes the COB on a long-term basis by issuing a Call for Participation. The responding organization(s) and the IAG Executive Committee shall then negotiate the Terms of Reference and other conditions.

(e) The President of the COB shall be elected by the IAG Council after consideration of a COB proposal.

(f) Major decisions related to the operations of the COB shall be made by a Steering Committee consisting of the following voting members:
(i) COB President.
(ii) IAG Secretary General.
(iii) Editor-in-Chief of the Journal of Geodesy.
(iv) Editor-in-Chief of the IAG Symposia Series.
(v) Up to 5 other members appointed by the IAG Executive Committee on the recommendation of the President of the COB.

19. IAG Publications

(a) The IAG publications include the Journal of Geodesy, the IAG Symposia Series, the Geodesist's Handbook, the "Travaux de l'Association Internationale de Géodésie," the IAG Newsletter, and IAG Special Publications.

(b) The Association's journal is the Journal of Geodesy, hereinafter referred to as the Journal. The Journal is published monthly through an agreement between the Association and a publishing company, or by other arrangement approved by the IAG Executive Committee. The terms of any agreement for publication of the Journal shall be negotiated by the President of the Communications and Outreach Branch and ratified by the IAG Executive Committee.

(c) The Journal publishes peer-reviewed papers, covering the whole range of geodesy, including geodetic applications.

(d) After each IAG General Assembly, a special issue of the Journal shall be published under the name of "The Geodesist's Handbook". This issue provides the actual information on the Association, including the reports of the IAG President and Secretary General presented at the previous IAG General Assembly, the resolutions taken at that assembly, and the Association structure listing all components and subcomponents for the running period, rules for the IAG Fund, IAG Awards and for the conduct of scientific meetings as well as relevant scientific information.

(e) The IAG Symposia Series publishes peer-reviewed papers related to presentations made at IAG Symposia and/or IAG Sponsored Symposia, provided that sufficient number of papers are submitted and accepted for publication.

(f) After each IAG General Assembly, a collection of the reports by the Association components shall be published in the "Travaux de l'Association Internationale de Géodésie". This publication is supplied free of charge to the officers of the Association and to the adhering body of each member country.

(g) At every IAG General Assembly each member country is encouraged to submit a National Report on geodetic work done since the previous General Assembly to be placed on the IAG website.

(h) The IAG Newsletter is under the editorial responsibility of the Communication and Outreach Branch. It should be published on the IAG website and distributed to members electronically.

20. Editor-in-Chief and Editorial Board

(a) There shall be one Editor-in-Chief for the Journal of Geodesy, hereinafter referred to as the Journal Editor. An Assistant Editor-in-Chief may assist the Journal Editor. The Journal Editor shall be advised and assisted by an Editorial Board. To ensure broad expertise, each of the Commissions may nominate up to three members of the Editorial Board.

(b) The Journal Editor shall be responsible for the scientific content of the Journal. The Journal Editor shall make the final decision on whether a refereed scientific manuscript is accepted for publication. The Journal Editor shall keep the IAG Executive Committee informed of the activities and status of operations of the Journal.

(c) Three months before each IAG General Assembly, the Journal Editor, in consultation with the IAG Bureau, shall recommend a preliminary list of candidates for the new Editorial Board. This list shall be published on the IAG website at least two months in advance of the IAG General Assembly to solicit additional nominations for the Editorial Board from the IAG Components, Members, Fellows, Honorary Offices, and Council.

(d) At the IAG General Assembly, the current Editorial Board shall appoint the members of the new Editorial Board from those recommended. After taking office, the new Editorial Board shall nominate the new Journal Editor and the new Assistant Editor for the next period. After approval of these nominations by the IAG Executive Committee, the Journal Editor and the Assistant Editor will be considered as elected.

(e) The Journal Editor, the Assistant Editor, and the members of the Editorial Board shall each hold office for one period, but are eligible to be re-elected for one further period.

(f) There shall be one Editor-in-Chief for the IAG Symposia Series, hereinafter referred to as the Series Editor. He/she is appointed by the IAG Executive Committee for one period. An assistant Editor-in-Chief may also be appointed.

(g) The Series Editor shall be responsible for the scientific content of the IAG Symposia Series. On the recommendation of the volume editor(s), the Series Editor shall make the final decision on whether a refereed scientific manuscript is accepted for publication. The Series Editor shall keep the IAG Executive Committee informed of the activities and status of the IAG Symposia Series.

(h) Each volume of the IAG Symposia Series may have additional Volume Editors.

21. IAG Individual Membership

(a) Individuals engaged in geodesy, can become individual members of the IAG on application and payment of the membership fee.

(b) Applications for individual membership are submitted to the IAG Secretary General.

(c) The decision on the membership application shall be made by the IAG Bureau.

(d) Benefits of membership include:

  (i) Reduction in the individual subscription rate to the Journal of Geodesy.
  (ii) The right to participate in the IAG election process both as a nominator and a nominee.
  (iii) Upon application, correspondent membership in a Sub-commission or Study Group of choice.
  (iv) Reduction in the registration fee for IAG meetings as set under Bylaws 26(d) and 27(b).

(e) The membership fee per annum is set by the IAG Executive Committee.

(f) In individual cases, the Secretary General may consider a discount or full remission of membership fees on application by the member.

(g) Where a member provides a donation in excess of the membership fee, the excess shall be assigned to the IAG Fund.

(h) Membership is terminated if the membership fee is not paid or if an application for discount or full remission has not been received one year after the fee was due.

22. Honorary Officers, Fellows

(a) The IAG Executive Committee may appoint a merited past IAG President as Honorary President or a merited IAG Secretary General as Honorary Secretary General.

(b) The IAG Executive Committee may appoint past officers of the IAG as Fellows.

23. IAG Fund

The IAG Executive Committee may establish an IAG Fund for supporting specific IAG activities as defined in the IAG Fund Rules, published in the Geodesist's Handbook. The Fund is under the direct responsibility of the President. The Fund's resources are administered by the Secretary General.

24. IAG Awards

The IAG Executive Committee may establish Awards for outstanding contributions to geodesy and distinguished service to the IAG. The rules for the awards are to be published in "The Geodesist's Handbook".

25. Administration of the IAG General Assemblies

(a) The IAG General Assembly will be held at the same time and at the same place as the International Union of Geodesy and Geophysics (IUGG) General Assembly.

(b) Before any IAG General Assembly, the IAG Bureau shall prepare detailed agendas for the IAG Council meetings, IAG Executive Committee meetings, and the opening and closing sessions.

(c) The IAG Executive Committee shall draw up the agenda for the scientific program. Joint Symposia covering topics of interest to two or more IUGG Associations may be arranged.

(d) The agendas developed according to (b) and (c) above are sent to the member countries and to all officers of the Association so as to reach them at least two months prior to the IAG General Assembly. In principle, only matters on the agenda may be considered during the sessions, unless a decision to do otherwise is passed by a two-thirds majority of the IAG Council.

(e) At each IAG General Assembly, the IAG President shall present a report on the scientific work of the Association during their tenure. The IAG Secretary General shall present a report on the administrative work and on the finances of the Association for the same period. The President and Secretary General should include in their reports proposals for work to be undertaken during the coming period, within the limits of expected resources. These reports shall be published in "The Geodesist's Handbook".

(f) At each IAG General Assembly, the work of each Commission, each Inter-commission Committee, each Service, the Communication and Outreach Branch, and each IAG Project shall be reported on by its President or Chair. IAG Representatives to other scientific bodies shall report to the IAG Executive Committee.

26. Scientific Meetings

(a) Scientific meetings of the IAG are:

- (i) the Scientific Symposia held during an IAG General Assembly;
- (ii) Scientific Assemblies, including IAG Scientific Symposia; and
- (iii) IAG Sponsored Symposia.

(b) The IAG Newsletter shall include a calendar of IAG Symposia and other scientific meetings organized or sponsored by the IAG or its components.

(c) The IAG Executive Committee shall appoint an IAG Scientific Meeting Representative for each of the scientific meetings other than the General Assembly and the Scientific Assembly to be governed by these Bylaws. The representative is obliged to remind the organizers to adhere to the Bylaws for scientific meetings and to report back to the IAG Executive Committee.

(d) A reduced registration fee shall be offered for individual members in accordance with Bylaw 21(d) (iv).

27. IAG Scientific Assemblies

(a) IAG Scientific Assemblies are held mid-way during the period between two IAG General Assemblies and shall consist of a group of component meetings and/or a group of scientific symposia, held at the same time and place.

(b) A reduced registration fee shall be offered for individual members in accordance with Bylaw 21(d)(iv).

28. IAG Scientific Symposia

(a) Scientific symposia take place at the IAG General Assembly and the IAG Scientific Assembly. In general, they shall be organized by IAG components and subcomponents, and be led by their respective Presidents or Chairs.

(b) The study of some questions may require joint meetings of several components under a chair, appointed by the IAG Executive Committee. A committee consisting of the component chairs shall decide on the agenda and on the inclusion of scientific presentations.

(c) At each IUGG General Assembly Joint Scientific Symposia covering topics of interest to two or more Associations within the IUGG and/or other international scientific organizations may be convened. Though the IAG may be asked to act as convenor or co-convenor, these symposia shall follow the rules established by the IUGG. The IAG may participate also in joint symposia at any other time outside of the IAG General Assembly and governed by the same procedures.

(d) The planning of a scientific symposium shall be subject to the usual approval procedure provided by "The Geodesist's Handbook".

29. IAG Sponsored Symposia

(a) The IAG may sponsor a symposium covering broad parts of geodesy and having large attendance at any suitable time outside the IAG General Assemblies or IAG Scientific Assemblies, and shall call it an IAG Sponsored Symposium, provided the following conditions are fulfilled:

  (i) One or more IAG component or subcomponent, or at least two Study Groups, shall sponsor it.
  (ii) Host organization of the symposium shall accept an IAG representative in the Scientific Organizing Committee (SOC) appointed by the IAG Executive Committee.
  (iii) The symposium shall be open to all bona-fide scientists in accordance with the International Science Council (ISC) rules.

(b) The SOC appointed under Bylaw 29(a)(ii) shall be responsible for the quality of science of the symposium being at a high level. A Local Organizing Committee (LOC) shall be responsible for the organization and logistics.

(c) Applications for approval of an IAG Symposium should be submitted to the Secretary General at least one year before the intended date of the meeting.

30. International Cooperation

(a) The IAG may participate in joint bodies of the IUGG and other scientific organizations, especially those belonging to the ISC.

(b) The IAG shall initiate international cooperation in scientific work of international and interdisciplinary character. This includes the adequate participation in international programs and projects and the representation at scientific congresses, symposia, etc., of organizations with related activities.

(c) Representatives to international programs and projects shall be appointed by the IAG Executive Committee and shall inform the IAG Executive Committee on the activities, on a biannual basis. The representatives shall also prepare a report for presentation at the IAG General Assembly.

(d) The IAG Components shall have close cooperation with inter-governmental organizations responsible for services and scientific products of particular interest to the Association (e.g. BIPM, ISO, UNOOSA/ ICG).

31. Responsibilities of the IAG Council

(a) In addition to any other functions, powers and duties provided in other Statutes and Bylaws, the IAG Council shall:

  (i) Examine questions of general scientific policy or administration, and propose actions deemed necessary.
  (ii) Elect the voting members of the IAG Executive Committee, with the exception of the GGOS Chair (Bylaw 15(d)) and the ICC Presidents, (Bylaw 17(b(i))).
  (iii) Receive reports from the Secretary General and consider for approval the decisions or actions taken by the IAG Bureau and the IAG Executive Committee since the last IAG Council meeting.
  (iv) Set up and dissolve IAG components.
  (v) Appoint the three members of the ad hoc (audit) committee created for examining the finances of the IAG, consider its recommendations and adopt the final budget.
  (vi) Consider proposals for changes in the IAG Statutes and Bylaws.
  (vii) Decide on the venue of the next IAG Scientific Assembly.
  (viii) Approve the establishment of Inter-commission Committees and IAG Projects.

(b) IAG Council meetings shall be convened by the IAG President, and shall meet at least once during each IAG General Assembly. The IAG Council may be convened at other times, normally coinciding with the IAG Scientific Assembly according to Statute 13(b).

32. Responsibilities of the IAG Executive Committee

(a) In addition to any other functions, powers and duties provided in other Statutes and Bylaws, the IAG Executive Committee shall:

(i) Initiate actions and issue guidelines, as required, to guide the IAG towards the achievement of its scientific objectives.
(ii) Fill vacancies occurring between IAG General Assemblies, in accordance with the Statutes and Bylaws.
(iii) Approve the internal structure of IAG components.
(iv) Make recommendations to the IAG Council on matters of general policy of the IAG and on the implementation of its objectives.
(v) Appoint Honorary Officers and Fellows of the IAG, upon the recommendation of the IAG Bureau.
(vi) Appoint planning groups for Inter-commission Committees and IAG Projects.
(vii) Establish Inter-commission Committees and IAG Projects.
(viii) Appoint a Committee, known as the Cassinis Committee, for reviewing and updating the IAG Statutes and Bylaws when deemed necessary.
(ix) Confirm the Assistant Secretaries (if any) of the IAG.
(x) Confirm the links between Commissions and Services.
(xi) Approve the level of the membership fee.
(xii) Appoint the Vice President of each Commission, the President of GGOS, and the President of each ICC.
(xiii) Appoint representatives to external bodies.

(b) IAG Executive Committee meetings shall be convened by the IAG President. It shall meet at IAG General Assemblies and its members are expected to attend the meetings of the IAG Council, with voice but without vote. It shall also meet normally at least once a year, especially one year before the IAG General Assembly, in order to prepare the scientific agenda and timetable of the next IAG General Assembly.

(c) At a meeting of the IAG Executive Committee, no member may be represented by any other person, except by the corresponding Vice Presidents or Vice Chairs of the IAG components represented in the Executive Committee. In order that the deliberations of the IAG Executive Committee shall be valid, a quorum of at least half of its members must be present or represented.

(d) The agenda for each meeting of the IAG Executive Committee shall be prepared by the IAG Bureau and sent to the members at least two months prior to the meeting.

33. Responsibilities of the IAG Bureau

(a) In addition to any other functions, powers and duties provided in other Statutes and Bylaws, the IAG Bureau shall:

(i) Draw up the agenda of the meetings of the IAG Council and IAG Executive Committee and send these to the members at least two months prior to the meeting.
(ii) Ensure the adequate administration of the IAG.
(iii) Receive applications for individual memberships and accept individuals as members of the IAG.
(iv) Recommend Honorary Officers and Fellows to the IAG Executive Committee.

(b) The IAG Bureau shall normally meet before each meeting of the IAG Executive Committee.

34. Responsibilities of the President

In addition to any other functions, powers and duties provided in other IAG Statutes and Bylaws, the IAG President shall:

(a) Provide general leadership for the IAG in all matters.

(b) Convene and preside over the IAG General Assembly and over all meetings of the IAG Council, IAG Executive Committee and IAG Bureau.

(c) Represent the IAG in IUGG meetings and forums.

(d) Represent the IAG in its dealing with national or international organizations or institutions.

(e) Submit a report to the IAG General Assembly on the scientific work of the IAG during their tenure.

35. Responsibilities of the Vice President

In addition to any other functions, powers and duties provided in other IAG Statutes and Bylaws, the IAG Vice President shall act on behalf of the IAG President whenever the IAG President is not present or is unable to perform any of the President's duties, and shall perform such tasks as may be assigned by the IAG President, the IAG Executive Committee or the IAG Council.

36. Responsibilities of the Secretary General

In addition to any other functions, powers and duties provided in other IAG Statutes and Bylaws, the IAG Secretary General shall:

(a) Serve as secretary of the IAG General Assembly, the IAG Scientific Assembly, the IAG Council, the IAG Executive Committee and the IAG Bureau; and arrange for meetings of these bodies, distribute promptly the agenda and prepare and distribute the minutes of all their meetings.

(b) Act as Director of the IAG Office.

(c) Manage the affairs of the IAG, including finances as per Bylaw 42(b), attend to correspondence, and preserve the records.

(d) Circulate all appropriate information related to the IAG.

(e) Prepare the reports of the IAG's activities.

(f) Coordinate with the COB.

(g) Perform such other duties as may be assigned by the IAG Bureau.

(h) The function of the Secretary General is unpaid and only expenses incurred in connection with the functions and duties may be reimbursed.

37. Assistant Secretaries

(a) The IAG Secretary General may be assisted by one or more Assistant Secretaries.

(b) The position(s) of Assistant Secretary is unpaid and only expenses incurred in connection with the functions and duties may be reimbursed.

38. IAG Office

To assist the IAG Secretary General, the IAG establishes the IAG Office in the country in which the Secretary General resides. The IAG Executive Committee negotiates logistical and financial support with the host country or institution.

39. Procedure for Nomination and Election of IAG Officers

(a) Elections shall take place by electronic voting before each IAG General Assembly and should be completed at least two months before the assembly.

(b) The IAG President, after taking advice from the IAG Executive Committee, shall appoint a Nominating Committee consisting of a Chair and three other members.

(c) The Nominating Committee, after taking advice from the Delegates of the Adhering Bodies, the Officers, Fellows, and Members of the IAG, shall normally propose at least two candidates for each position to be filled by election of the IAG Council. Candidates shall be asked to signify their acceptance of nomination and to prepare a short resume, outlining their position, research interests and activities relating to the IAG.

(d) The Adhering Bodies and the individual membership shall be informed of these nominations at least four months before the IAG General Assembly.

(e) During the following month further nominations can be submitted by the Delegates of the Adhering Bodies. Such additional nominations shall be in writing, shall be supported by at least two members of the IAG Council, and shall be submitted with resumes to the Chair of the Nominating Committee.

(f) Nominations shall be checked against the eligibility criteria in Bylaw 40 by the Nominating Committee. Ineligible nominations will not be accepted and the members of the IAG Council who supported the nomination will be advised of the reason for its rejection.

(g) Delegates shall be informed of these further eligible nominations and resumes and of their supporters.

(h) The Chair of the Nominating Committee shall write to all Services asking them for nominations from each Service for the Service representatives on the IAG Executive Committee. The Nominating Committee shall recommend a minimum of two nominees for each of the Services' three positions, considering appropriate scientific and geographic distribution. The procedure for seeking additional nominations in subclause (e) above does not apply to these positions.

(i) If candidates have been nominated for more than one position, they will be asked prior to the election to make a decision for which position they will allow their name to stand.

(j) Elections shall be by electronic ballot. The winner must receive an outright majority (number of votes being greater than the total combined votes of the other candidates). If there are three or more candidates for a position and no candidate has an outright majority, then the top two ranked candidates will be retained and a second round of votes conducted to elect the winner. Ties will be broken by the IAG President's vote.

(k) The Members-at-Large shall be elected in a subsequent round after the other members of the IAG Executive Committee have been elected, in order to fulfil the condition of geographical, gender and organizational balance (see Statute 12a).

40. Eligibility & Terms of Office

(a) No person may hold more than one of the following offices at the same time: IAG President, Vice President, Secretary General, IAG immediate Past President, President of a Commission, President of an Intercommission Committee, Chair of a Service, President of GGOS, President of the COB, Executive Committee Member-at-Large, or Chair of an IAG Project.

(b) A member of the IUGG Bureau or of the IUGG Finance Committee may not occupy the post of President, Vice President or Secretary General of the IAG.

(c) The IAG President is elected for one period and may not be immediately re-elected to the same office.

(d) The Vice President is elected for one period and may not be re-elected to the same office.

(e) The Secretary General is elected for one period initially. He/she may be re-elected for up to two additional periods.

41. Extraordinary Vacancies

(a) Should the position of IAG President become vacant during the period between two IAG General Assemblies, their duties and responsibilities devolve to the Vice President until the closure of the next IAG General Assembly.

(b) Should the post of Secretary General become vacant, the IAG President shall arrange without delay for the IAG Executive Committee to propose a replacement and for the IAG Council to appoint a new Secretary General so as to ensure the continuity of the work of the IAG Office. This appointment has effect until the closure of the next IAG General Assembly and shall not be counted in the restriction of eligibility for re-election of the Secretary General under Bylaw 40(e).

42. Finances

(a) The Finances of the IAG derive from the following sources:

(i) Contributions of IUGG Adhering Bodies of which a portion, determined by the IUGG Council on recommendation of its Finance Committee, is paid to the IAG by the IUGG Treasurer.
(ii) Sale of publications.
(iii) IAG Fund collected from individual contributions for specific purposes.
(iv) Membership fees.
(v) A portion of the registration fee charged at IAG symposia.
(vi) Other sources, e.g. grants, interests, and funds remaining after a symposium.

(b) The Secretary General is responsible to the IAG Bureau and to the IAG Council for managing the funds in accordance with the Statutes and Bylaws. The Secretary General alone shall be responsible for the day-today financial operations of the IAG.

(c) At each IAG General Assembly the budget proposal for the next period shall be presented by the Secretary General and submitted for approval to the IAG Council. The budget as approved by the IAG Council shall be implemented by the Secretary General.

(d) During each IAG General Assembly, the IAG Council shall examine all expenditures during the preceding period to ensure that they were in accordance with the approved budget. This examination shall be carried out by an ad hoc (audit) committee appointed by the IAG Council; see also Bylaw 31(a)(v).

(e) In addition, the accounts shall be audited and shall then be reported to the IUGG Treasurer, as prescribed in Article 20 of the IUGG Bylaws.

Rules for IAG Scientific Meetings

1. IAG scientific meetings are organized by IAG components (Commissions, Inter-commission Committee on Theory, Services, and the Global Geodetic Observing System) or IAG Sub-components (Sub-commissions, other Inter-commission Committees, Projects, Study Groups, Working Groups). They may take place:
   a) during IAG General Assemblies, held in conjunction with the IUGG General Assemblies,
   b) during IAG Scientific Assemblies, held in-between successive General Assemblies, or
   c) at any time and place apart from the General or Scientific Assemblies.

2. During the General or Scientific Assemblies symposia and other meetings are in general organized by IAG components or sub-components. For specific topics there may be joint symposia of several components or sub-components under a convener appointed by the IAG Executive Committee. The inclusion of scientific papers for presentation at a General or Scientific Assembly is decided by a Scientific Committee established by the IAG Executive Committee.

3. At General Assemblies joint symposia covering topics of two or more Associations within the Union and/or other international scientific organizations may be organized. Though the IAG may act as convener or co-convener, these symposia follow the IUGG rules.

4. The IAG may participate also in joint symposia with other Associations at any other time outside of the General Assemblies, following the same procedures.

5. The IAG may sponsor symposia covering appropriate topics of Geodesy at any time outside of the General or Scientific Assemblies. It shall be called IAG sponsored Symposium if the following conditions are fulfilled:
   - The symposium has to be organized by at least one component or two sub-components of the IAG.
   - The host organization of the symposium must accept a representative in the Scientific Organizing Committee (SOC) appointed by the IAG Executive Committee.
   - The symposium must be open to all bonafide scientists in accordance with the ICSU rules.
   - The proceedings of the symposium shall be published.
   - If there is a registration fee, it must be reduced for IAG members by at least 10%.
   - Immediately after the end of the Symposium the chairperson of the Scientific Committee shall prepare a summary to be published in the IAG Newsletter.

6. Applications for approval to be designated IAG Symposium should be submitted to the Secretary General of the IAG at least twelve months before the proposed date of the Symposium. The following information must be provided in the application for approval:
   a) Title,
   b) Date and duration,
   c) Location,
   d) Sponsoring IAG (Sub-) components,
   e) Other co-sponsoring scientific organizations with letters enclosed,
   f) Suggested composition of the Scientific Organizing Committee,
   g) Local Organizing Committee, host organization, name and address of contact, etc.
   h) Estimated number of participants,

i) Financial support expected from sources other than the IAG,

j) Names of the proposed editors of proceedings,

k) Draft scientific program,

l) A detailed account of why the proposed symposium is useful and necessary at the time proposed, and its relationship with other meetings.

7. Guidelines for the organization of the symposium:

a) The Scientific Organizing Committee is responsible for ensuring a high standard of scientific value of the symposium. The chair of the Committee:

- invites participants after the symposium is approved by the IAG Executive Committee,
- invites contributions and sets a deadline for submissions of abstracts, and
- informs the IAG Secretary General of all important matters pertaining to the symposium.

b) The Local Organizing Committee is responsible for the smooth running of the symposium. It does not receive financial assistance from the IAG, with all the necessary expenses being met by local funds or by contributions from the participants. The requirements of local organizations are generally as follows:

- providing meeting rooms suitable for the expected number of participants,
- providing the facilities for oral and visual presentations,
- provide adequate space and logistical support for poster sessions (if any),
- reproduction of participants' document (if necessary), organize publication of proceedings or production of CD version,
- sufficient secretarial and technical assistance,
- undertake full responsibility for registration of participants, maintaining a web page, printing of brochures and programmes, etc.
- information on accommodation (hostels, hotels, etc...), sent to the IAG Executive Committee for acceptance, and to prospective participants,
- organizing receptions and excursions during a free period within the meeting, or just before or after the meeting.

8. The IAG Executive Committee shall recognize scientific meetings other than symposia (workshops, etc.) organized by IAG (Sub-) Components, alone or jointly with other international and national groups and bodies, at any time outside of the General Assemblies, if they have been approved by the Executive Committee. The Meeting may be announced as "International Meeting, organized by the .... of IAG". It is not permitted to use the term "IAG Symposium".

9. The IAG may recognize scientific meetings, organized by national bodies as important scientific events with benefit for the international geodetic community, and sponsor them if the meeting is open to all scientists according to the ISC Rules, and will be sponsored by at least one IAG (Sub-) Component, and if the organizer undertakes to maintain the expected standard for IAG-Symposia.

These Meetings may be announced as "International Meeting, organized by ....., sponsored by IAG". It is not permitted to use the term "IAG Symposium". Sponsorship by the IAG means only official recognition and does not imply financial support by the IAG. The IAG may appoint an official representative to that meeting. The IAG expects that, in the event that proceedings are published, the Proceedings will be prepared by the local organizers and published within 6-8 months after the end of the meeting.

Applications for sponsorship should be submitted to the IAG Secretary General not later than 12 months before the intended date of the meeting.

10. In its decision whether to approve and/or sponsor a scientific meeting, the IAG Executive Committee takes into account the need for a balanced selection of meetings, a representative coverage of subjects, and a good geographical distribution. The IAG wishes to avoid duplication of symposia or meetings, and to discourage symposia or meetings with overlapping themes that are held with too high a frequency.

The IAG Secretary General shall publish a calendar of IAG Symposia and other scientific meetings organized or sponsored by IAG components or sub-components in the IAG Newsletter, in the Journal of Geodesy, and on the IAG Website.

Rules for the IAG Levallois Medal

Purpose

The Levallois Medal was established by the International Association of Geodesy in 1979 to honour Jean-Jacques Levallois, and to recognize his outstanding contribution to the IAG, particularly his long service as Secretary General, 1960-1975.

The award of the Medal will be made in recognition of distinguished service to the Association, and/or to the science of geodesy in general.

The Medal is normally awarded at four year intervals, on the occasion of the General Assemblies of the International Association of Geodesy and International Union of Geodesy and Geophysics; but the award may be omitted if it is considered that there is no candidature of sufficient merit, and an additional award may be made at any time if justified by exceptional circumstances.

Nomination and Election

A nomination for the award shall be made by an ad hoc committee consisting of the Honorary Presidents and must be confirmed by the IAG Executive Committee. The ad hoc committee shall prepare a citation, suitable for publication, setting out the grounds for the proposed award before the General Assembly.

Rules for the IAG Guy Bomford Prize

Purpose

The Guy Bomford Prize is awarded by the International Association of Geodesy for outstanding contribution to Geodesy. It was established by the British National Committee for Geodesy and Geophysics to mark the contributions to geodesy of Brigadier *G. Bomford*, formerly of the University of Oxford and a Past President of the International Association of Geodesy. It has been inaugurated by the IAG in 1975. The Prize is normally awarded at intervals of four years on the occasion of the General Assembly of the IAG held concurrently with the General Assembly of the International Union for Geodesy and Geophysics. The following rules for the award of the Guy Bomford Prize may be altered by the IAG Executive Committee if a majority of its voting members sees a necessity to do so.

Eligibility

The Guy Bomford Prize is awarded to a young scientist or to a team of young scientists for outstanding theoretical or applied contributions to geodetic studies particularly in the four year period preceding the General Assembly at which the award is made. Scientists who are under 40 years of age on December, 31, of the year preceding the Assembly at which the award is made, are eligible for the award.

Nominations

Nominations will be invited by the IAG Bureau from all National Committees of IUGG member countries at least one year ahead of the General Assembly. Each committee can make one nomination which has not necessarily to be from its own country. The deadline for nominations will normally be six months before the next General Assembly and will be explicitly started in the letter of invitation.

Nominations must be accompanied by:

- The full name, address, age, academic and/or professional qualifications and position of the candidates and the name of the National Committee making the nomination.
- An outline of the reasons for the nomination including a general summary of the career and scientific achievement of the candidate.
- A review of recent achievements of the candidates which would merit the award, including references to key papers, published, alone or jointly, during the preceding four-year period.
- A curriculum vitae, publication list, and copies of up to two key papers which are considered to justify candidature.
- The name and address of two referees who can be consulted.

Selection procedure

A selection committee will be appointed consisting of the presidents of the IAG commissions and two other members to be appointed by the IAG Bureau. Based on the material submitted by the National committees each member of the selection committee will rank the nominations and select the candidate to be awarded the Guy Bomford prize. The decision (not the detailed ranking) will be communicated to all National Committees and to the selected candidate. The prize may be withheld if, in the opinion of the selection committee, there is no sufficiently qualified candidate available.

Presentation of award

The Prize shall be presented to the successful candidate at the opening Plenary Session of the IAG Assembly. He or she shall be invited to deliver a lecture during the course of the IAG Assembly.

Rules for the IAG Young Authors Award

Purpose

The award is to draw attention to important contributions by young scientists in the Journal of Geodesy and to foster excellence in scientific writing.

Eligibility

The applicant must be 35 years of age or younger when submitting the paper for the competition. The paper must present his or her own research, and must have been published in the two annual volumes of the Journal of Geodesy preceding either the IAG General Assembly or the Scientific Assembly. Although multiple author papers will be considered, single author papers will be given more weight in the selection process.

Award

The award consists of a certificate and a cheque of US $ 1000. Presentation of the awards will be made at each IAG General Assembly and each Scientific Assembly. Up to two awards will be presented on each occasion for the two-year period corresponding to the annual volumes specified above.

Nomination and Selection

For each two-year period the Editor-in-Chief of the Journal of Geodesy will propose a minimum of three candidates for the award. In addition, proposals made by at least three Fellows or Associates will be considered for the competition. The voting members of the IAG Executive Committee will make the final selection. It will be based on the importance of the scientific contribution, which may be either theoretical or practical, and on the quality of the presentation. The name and picture of the award winner and a short biography will be published in Journal of Geodesy.

Procedure

Each year the conditions for the award will be announced in the Journal of Geodesy. Nominations should be sent to the Secretary General of the IAG, giving name, address, and age of the author (at date of submission), the title of the paper on which nomination is based, and a brief justification. Nominations must be received by March 1 of the year in which either an IAG General Assembly or an IAG Scientific Assembly takes place.

Rules for the IAG Travel Awards

Purpose

The award is established to assist young scientists from IAG member countries to present results of their research at IAG meetings (assemblies, symposia, workshops, etc.).

Eligibility

The applicant must present results of his or her research at the meeting and must be 35 years of age or less at the date of the application. The application must be supported by at least one IAG Fellow or two Associates.

Type of awards

There are two awards, one for meetings in the applicant's own country, and the other for meetings outside the applicant's country. The first is called *IAG National Travel Award* and has a maximum financial value of 750 Euros. It is available for meetings in developing countries. The second is called *IAG International Travel Award* and has a maximum financial support of 1500 Euros. The amounts can occasionally be adjusted by the IAG Executive Committee. It was adjusted last in 2020.

Additional benefits

The IAG will encourage the organizers of the meetings to waive the registration fees for all IAG Travel award winners.

Application procedure

Applicants shall send their application **at least three months before the meeting** to the IAG Secretary General, iag.office@nls.fi.

The application must contain:

- Full name of the Applicant, address and e-mail address
- Institution and degree/position (e.g. University XX, PhD Student)
- Date of birth
- IAG meeting name, city, country, date
- Title, authors, and abstract of the paper to be presented
- A letter of acceptance of the presentation by the organising committee (if available, otherwise it has to be submitted as soon as it is available)
- Travel budget and sources of additional funding
- Name(s) of supporting person(s); the letter(s) of support (either from an IAG Fellow or from two Associates) should be sent separately by the supporter(s).

By sending the application, the applicant agree that his/her data are stored internally in the IAG records. Data are used only for Award-related purposes.

Selection procedure and criteria

Selection of applicants and the amount granted will be done by the IAG Bureau. It will be based on the paper to be presented, the letter(s) of support, and the applicant's ability to actually attend the meeting. Priority will be given to candidates from developing countries. IAG Secretary General will agree with winners the details of the payment. Normally it cannot be paid before the meeting.

IAG Fund

The IAG Fund aims at supporting specific IAG activities. Its primary goals are:

- to provide travel support for young scientists to attend IAG Symposia and workshops,
- to assist in the organisation of IAG workshops in developing countries, and
- to provide an annual IAG Best Publication Award for young scientists.

The fund was established by the IAG Executive Committee at its meeting in Columbus, Ohio, 1992, see Bulletin Géodésique, Vol. 68, pp. 41-42, 1994.
Contributors are divided in 3 groups:

- Presidents Club (cumulative contributions of US $ 1000 and more or equivalent in EUR)
- Special contributors (annual contributors of US $ 100 … US $ 1000 or equivalent in EUR)
- Contributors (annual contributions of less than US $ 100 or equivalent in EUR)

The rules for the IAG Young Authors Award and for the IAG Travel Award for young scientists are given in a separate section of the Geodesist's Handbook. The application forms can be found at the IAG Website.

How to Donate

In connection of the membership fee: In the membership fee form there is a specific place for donations. The donation can be of any amount; however, in case of donations US $ 100 (or equivalent in EUR) or more, please send additionally a notice to the IAG Secretary General.

Donations paid separately: The payment can be made using the same form as the donations in connection of the membership fee. Please, contact IAG Secretary General in advance.

The membership application / donations form can be found at the IAG Website https://www.iag-aig.org. Direct link: https://www.iag-aig.org/doc/IAG_Membership_Application_Form.pdf.

IAG Membership

Individuals engaged in geodesy, can become individual members of the IAG on application and payment of the membership fee. Applications for individual membership are submitted to the IAG Secretary General.

Benefits of membership include:

- Reduction in the individual subscription rate to the Journal of Geodesy.
- The right to participate in the IAG election process both as a nominator and a nominee.
- Upon application, correspondent membership in a Subcommission or Study Group of choice.
- Reduction in the registration fee for IAG meetings

The membership fee per annum is set by the IAG Executive Committee. In individual cases, the Secretary General may consider a discount or full remission of membership fees on application by the member. There are two specific cases mentioned on the membership fee form:

- ***Student membership***: Students in Universities/Colleges will have annual free membership of IAG. They must submit University/College certificate separately every year to the IAG Secretary General to get the benefit.
- ***Retired members***: Retired people shall send a request to the Secretary General for getting the exemption.

How to pay

The application form and instructions for the payment can be found at the IAG web page. The payment can be made either by a bank transfer or with a credit card.

The payment can be for one calendar year or four years. To minimize possible transfer fees, more than one membership fee can be paid at the same time. In that case, the list of names/addresses shall be sent separately to the Secretary General.

After reception of the payment, the certificate and receipt of the payment will be sent by e-mail to the address given by the member.

In case of any issues or questions, please send the request to the Secretary General.

The membership application form can be found at the IAG Website https://www.iag-aig.org. Direct link: https://www.iag-aig.org/doc/IAG_Membership_Application_Form.pdf.

The XXVII IUGG General Assembly, Montreal, Canada, 2019
IAG Presidential Address

Harald Schuh
GFZ German Research Centre for Geosciences,
Telegrafenberg, 14473 Potsdam, Germany
schuh@gfz-potsdam.de

Dear Guests and Colleagues, dear Ladies and Gentlemen,

I welcome you to the IAG General Assembly, taking place in Montreal on the occasion of the 27th General Assembly of the International Union of Geodesy and Geophysics (IUGG). Chairing this Opening Ceremony is one of my last responsibilities as outgoing IAG President. For IAG, the quadrennial 2015-2019 was a really dynamic and fruitful period. Together with many individuals of the various IAG Commissions, Services, and other components, we have pushed quite a number of new developments and IAG is in a very sound condition today. In Prague four years ago, *Chris Rizos*, then the outgoing President, gave a comprehensive overview presentation about the IAG, its internal structure and tasks. It is published in the Geodesist's Handbook 2016 and I encourage you to look there again. My report here I will make rather short and will just remind you of the most important highlights and innovations since 2015.

For the year 2016, internally, I would like to mention our forthcoming in the strategic planning process; in the outer, political sphere, the establishment of the United Nations Subcommittee on Geodesy was a real breakthrough for global geodesy. Both developments will help us to shape future IAG matters much more efficiently.

The IAG Executive Committee met for its third meeting in the term 2015-2019 at the GFZ German Research Centre for Geosciences in Potsdam, Germany, on April 25, 2016. At this meeting, the IAG final structure 2015-2019 of Commissions 1 – 4, of the Inter-Commission Committee on Theory, and of GGOS was decided. On the next day, an IAG Strategic Planning Retreat was conducted. It was mainly aimed at an IAG SWOT analysis and the following discussion to reveal the current state of the Association. SWOT stands for strengths, weaknesses, opportunities, and threats, and a great number of all of them were identified during the retreat. The retreat which was chaired by IAG Past President *Gerhard Beutler* took place in a very open-minded and intensive atmosphere.

Based on the retreat material, a guiding document was formulated that in turn was the basis for the draft strategy document to be discussed and approved at the next EC meeting in Vienna on April 28, 2017, and to be presented to the public, in particular to the IAG Council delegates, at the IAG Scientific Assembly in Kobe in July 2017. This long strategic planning process shall be completed here in Montreal were the IAG Council delegates will be requested for approval of the final version of the strategy document that can be found on https://office.iag-aig.org/iag-publications-reports-position-papers → IAG Strategy 2019.

During the first week of August 2016, the United Nations Global Geospatial Information Management (UN-GGIM) sixth session took place in New York which I attended representing the IAG. At this UN-GGIM conference, the UN Committee of Experts on Global Geospatial Information Management endorsed the GGRF (Global Geodetic Reference Frame) Roadmap and decided to establish a permanent Subcommittee on Geodesy. The suggestion to elevate the Working Group's mandate through the establishment of a UN-GGIM Subcommittee on Geodesy was put forward by New Zealand and the proposal was supported by several member states. The IAG welcomed and unreservedly appreciated the establishment of a United Nations Subcommittee on Geodesy. This advancement will augment the impacts of geodesy on the political level as well as its visibility in society. IAG and its Global Geodetic Observing System (GGOS) as promoting geodetic science and coordinating the international geodetic services will strongly support the new Subcommittee whenever necessary and wherever possible.

At the UN-GGIM sixth session in New York, the member states did also endorse the Roadmap for the Global Geodetic Reference Frame as a principle based briefing document for national governments. The Roadmap aims to enhance the GGRF and make it more sustainable. Today, the UN-GGIM Subcommittee on Geodesy consists of about 40 member states and five international and national organizations: besides IAG, they are the International Federation of Surveyors (FIG), SIRGAS Geocentric Reference System for the Americas, the World Health Organization (WHO), and NASA.

IAG developed a Position Paper that contains a description of the Global Geodetic Reference Frame and was adopted by the IAG Executive Committee in April 2016. The purpose of this document is a brief description of the GGRF key components as a realization of the Global Geodetic Reference System (GGRS) and it forms the basis for a common understanding of the GGRF. It thus outlines the IAG's perspective of what the GGRF is, and how it is realized through the contributions of the IAG components.

The Position Paper on the UN-GGIM Global Geodetic Reference Frame (GGRF) adopted by the IAG Executive Committee can be downloaded from https://office.iag-aig.org/iag-publications-reports-position-papers → Description of the Global Geodetic Reference Frame (GGRF) by the IAG.

In November 2016, at a meeting with the Springer publishing editor responsible for the IAG Series an important improvement regarding the IAG Symposia Series published by Springer was decided: The Series will be published immediately as eBook, i.e. go online. The procedure is a peer review as before, but each article is being published online a few days after the acceptance by the IAG Editor-in-Chief *Jeff Freymueller*.

IAG's top highlight of the year 2017 was the organization and effective running of the IAG/IASPEI Joint Scientific Assembly in Kobe, Japan, from July 30 through August 4, 2017. The business meetings during the IAG Scientific Assembly in Kobe comprised in particular three IAG Executive Committee Meetings, one IAG Bureau Meeting, and one IAG Council Meeting, and all went very efficiently. The EC's decision to establish new sub-components of IAG Commissions as inter-Association commissions, namely on Volcano-geodesy, Seismo-geodesy, and Cryosphere geodesy, and to establish the two new inter-Commission projects of IAG (on New technologies in geodesy and on Marine geodesy) were very timely.

Of the many IAG highlights of the year 2018, I would like to mention here only a tiny selection, in which I had the honor to participate: These are the successful launch of the German-American satellite mission GRACE-FO (Gravity Recovery and Climate Experiment Follow-On) aboard a SpaceX Falcon 9 rocket from the Vandenberg Air Force Base (California) on May 22, 2018, the inauguration of the new twin VLBI telescopes at Ny-Ålesund, Svalbard, Norway, on June 6th, 2018, the UN-GGIM conference week with several splinter meetings about the GGRF in New York in August 2018, and two very efficient IAG Executive Committee meetings, the first one in Vienna, Austria, during the EGU General Assembly on April 13, 2018 and the second one in Washington D.C., USA, during the AGU Fall Meeting on December 10, 2018.

At the Eighth Session of the United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM) held at the United Nations Headquarters in New York from 1 to 3 August 2018, the Roadmap for the Global Geodetic Reference Frame for Sustainable Development Implementation Plan presented by the UN-GGIM Subcommittee on Geodesy was discussed. IAG is participating as an observer in all meetings and related activities of UN-GGIM. At the session, IAG was represented by myself and *Michael Pearlman*, Chair of the GGOS Bureau of Networks and Observations. The IAG delegation made a well-noted intervention for the GGRF agenda item, comprising the following points:

> *The International Association of Geodesy commends the work done by the UN GGIM Subcommittee on Geodesy, and emphasizes that the Roadmap Implementation Plan is an important building block to determining a sustainable Global Geodetic Reference Frame.*
>
> *Together with its geodetic services, IAG encourages modernization of geodetic infrastructure, as well as development of Core Observatories, especially in developing regions.*
>
> *IAG notes that there is a clear need for strengthened intergovernmental mechanisms in support of global geodesy, and notes with appreciation the Subcommittee on Geodesy's efforts to provide this through a Convention or other possible governance mechanisms mentioned in the Position Paper on Governance.*
>
> *IAG encourages the establishment of funding mechanisms for global geodesy, in order to support geodetic infrastructure and education in developing Member States. IAG further notes that such funding will provide a means to strengthen the GGRF overall, as well as help realize the geodetic contributions to the UN Sustainable Development Goals and Sendai Framework for Disaster Risk Reduction.*

Four years ago, at our General Assembly in Prague, I presented to you in my inaugural speech as IAG President the vision, or call it dream or crazy idea, to establish a World Geodetic Organization (WGO) to implement geodetic infrastructure all over the world where it is really needed. That vision is not a dream anymore: In 2019, a Global Geodetic Center of Excellence (GGCE) is in planning process under

UN-GGIM. The proposal of creating a GGCE under the auspices of the United Nations receives strong support. With this element, the Subcommittee on Geodesy has reached a new milestone on the road towards a sustainable GGRF.

Concerning the IAG strategic planning process, the EC finalized the IAG Strategy Document in 2018 as planned. Several of the recommendations and action items postulated in the Strategy Document had already been realized by 2018. The EC decided, for instance, to establish planning groups of the new bodies within the IAG and also as inter-association entities, all to be established at IUGG2019 here in Montreal.

In the following, I will summarize some developments in IAG since 2015. These new entities in IAG were established (new inter-association joint (Sub-) commissions, IAG Projects, or IAG Intercommission Committees (ICC):

- with IASPEI ("Seismo-geodesy"), SC 3.5 from IAG
- with IAVCEI ("Volcano-geodesy"), SC 3.2 from IAG
- with IACS ("Cryosphere geodesy"), SC 3.4 from IAG
- new ICC on "Geodesy for climate research", approved (Chair: *A. Eicker*)
- new ICC on "Marine geodesy", approved (Chair: *Yangxi Yang*)
- new IAG Project on "Novel sensors and quantum technology in geodesy", approved (Chair: *J. Müller*),

the latter dealing with new technologies in geodesy such as quantum technology, optical clocks, and atom gravimeters. Regarding IAG Services, the International Geodynamic and Earth Tide Service (IGETS) was established and is in full operation since 2017 and the revitalization of the International Altimetry Service is under construction. The International Gravity Field Service (IGFS) has now its own, new Product Center on "Combination for Time-variable Gravity field solutions" which will certainly elevate the role and importance of the IGFS. The International Service for the Geoid (ISG) was renamed and had set up a new agreement with IAG.

As the observing system of the IAG, GGOS serves a unique and critically important combination of roles centering upon advocacy, integration, and international relations. In the last four years, GGOS has also experienced a dynamic development: In 2016, the new internal structure was confirmed, the new Coordinating Office was established at BEV, Austria, and the Terms of Reference were updated. In 2017, the new Focus Area 4, Geodetic Space Weather Monitoring, was enacted and *Michael Schmidt*, TU Munich appointed as Chair, the Bureau of Networks & Observations and the Bureau of Products & Standards began operations and *Richard Gross* took over GGOS chairmanship from *Hansjörg Kutterer*.

A few words on IAG publications. The ranking of the Journal of Geodesy with *Jürgen Kusche* as editor-in-chief increased significantly (IF 4.633 (2017) and 4.528 (2018)). The journal receives more than 300 submissions per year; the acceptance rate is 34%. In 2019, a Continuous Article Publishing (CAP) was decided.

The latest volumes of the IAG Symposia Series are Vol. 147, International Symposium on Earth and Environmental Sciences for Future Generations (2018), Vol. 148, International Symposium on Gravity, Geoid and Height Systems (2018), and Vol. 149, Joint IAG/IASPEI Scientific Assembly, Kobe, Japan, 2017 (2019) and another big step forward is that the IAG Symposia Series will change to open access starting with the upcoming 27th General Assembly.

IAG reports, annual and quadrennial reports, monthly IAG Newsletters, position papers, outreach documents that can be found on the IAG homepage at https://www.iag-aig.org are a vivid prove about the various activities of IAG components in the last four years.

The Geodesist's Handbook https://link.springer.com/ article/10.1007/s00190-016-0948-z provides information on the IAG history, statutes, bylaws, rules, and membership, a Report of the General Assembly 2015, and structure and program descriptions of the period 2015-2019.

Before coming to the end I have to provide the sad information that during the last quadrennial, the following former IAG officers and outstanding geodesists passed away:

2015: *Suriya Tatevian*, Russia, *Graciela Font*, Argentina, *Hermann Seeger*, Germany, *Camil Gemael*, Brazil, *John Wahr*, USA

2016: *Heinz Henneberg*, Venezuela, *Alexander Kopaev*, Russia

2017: *Klaus Linkwitz*, Germany, *Dieter Lelgemann*, Germany, *Olumuyiwa Adebekun*, Nigeria, *Barbara Kolaczek*, Poland, *Bernard Guinot*, France, *József Závoti*, Hungary

2018: *Marcin Barlik*, Poland, *Michel Louis*, France, *Hermann Mälzer*, Germany, *Yoshihide Kozai*, Japan, *Jean Dickey*, USA, *Jean Kovalevsky*, France, *Mikhail Prilepin*, Russia

I am coming now to the end of my talk, and of my term as IAG President. I have truly enjoyed doing this work for the past four years. I wish to thank all members of the outgoing IAG Executive Committee, and the many other colleagues who make vital contributions to the IAG Commissions, Services, and other components. Your support, your brightness, your commitment makes IAG the lively and learning organization that is counted on and that is listened to.

I wish the new Executive Committee that was elected by ballot prior to this General Assembly lots of success and stamina for the future! Thank you.

Levallois Medal Laudation for Christoph Reigber

Chris Rizos[1]

The Levallois Medal was established in 1979 to honour *Jean-Jacques Levallois* for his long service as General Secretary of the International Association of Geodesy (IAG) from 1960 to 1975. It is awarded on the occasion of the IAG General Assembly to a distinguished geodesist "in recognition of distinguished service to the Association and/or to the science of geodesy in general".

An ad hoc committee of past presidents of the IAG has recommended to award the Medal at the 2019 IAG General Assembly to Emeritus Professor *Christoph Reigber*, for his sustained service and leadership over several decades to the IAG and to geodesy in general.

Professor Harald Schuh handing over the Levallois Medal to Professor Christoph Reigber at GFZ (Photo: Markus Bradke, GFZ)

Christoph Reigber was born in 1939 in Breslau, in today's Poland. He completed his Diploma in Surveying and Geodesy in 1965 at the Technical University Munich. In 1969 Christoph completed his doctoral thesis at TUM, and obtained his Habilitation in 1974, also from the TUM. His subsequent university career included Professor in the Department of Astronomical and Physical Geodesy TUM 1982-1992, and Professor at the Institute of Earth and Environmental Sciences, Potsdam University, 1993-2004. He was made Emeritus Professor upon his retirement in 2004.

Christoph Reigber's most significant contributions to the IAG and to geodetic science are best exemplified by his extraordinary, and far-sighted leadership of numerous projects and several institutions, over a period spanning four decades. It is not possible to mention many of these in this Laudation, hence just a few will be highlighted.

Christoph was appointed Director of the Department "Theoretical Geodesy" at the Deutsches Geodetisches Forschungs Institut (DGFI – in English, the German Geodetic Research Institute) in Munich, in 1980, a position he held until 1992. During this period Christoph had two major influences on the activities and contributions of DGFI. The first was an increased focus on the technology and earth science applications of satellite geodesy. The second was a dramatically increased engagement with ESA (and other space agencies) in projects, being a co-investigator or principal investigator, undertaking theoretical studies in support of new geodetic technologies, as well as direct participation in satellite missions. These projects included CI for NASA's Laser Geodynamics Program, the spaceborne laser study SPALT, several POPSAT system studies, PRARE tracking technology studies, being an analysis centre for MERIT and MEDLAS campaigns, several gravity field mission studies, PI on the ERS-1 mission, to name the most significant. This strong leadership in promoting

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satellite geodesy, and a focus on developing cutting edge geodetic technologies and promoting new satellite missions, have been the dominant contributions of *Christoph Reigber* to geodesy, from his early days at DGFI, and subsequently at the GFZ.

Arguably Christoph's most important contributions to the IAG, and to geodesy in general, were made during his directorship at the Deutsches GeoForchungsZentrum (GFZ – German Research Centre for Geosciences). The GFZ is Germany's most significant investment in the geosciences in the latter half of the 20th century. Christoph was one of the handful of scientists with the courage and vision to imagine the total revitalization of the geosciences on Telegrafenberg, in Potsdam, shortly after the reunification of Germany. This included a new science-focused geodesy institute, the Department "Geodesy and Remote Sensing", one of five founding departments of the GFZ. This department could boast a heritage going back to the legendary Central Bureau established by Johann Jacob Baeyer following the first "General Conference of the Representatives to the Central European Arc Measurement" held in Berlin in 1864. This date and event is reckoned to be the foundation of the IAG, and it was fitting that we celebrated the 150th anniversary of the founding of the IAG in 2013 at the GFZ. This department was even located in the same building as the original bureau. Christoph was Director of the department from 1992 until his retirement at the end of 2004.

While at the GFZ Christoph was able to launch a number of initiatives, whose significance is still considerable. One was to establish a GPS Analysis Centre at the GFZ that became one of the first ACs for the IGS when it was formally launched as an IAG service on 1 January 1994. Christoph was also Project Manager for the GFZ-1 geodynamic satellite mission. Perhaps his most far-reaching contributions to geodetic science have been in the field of satellite gravity missions. Christoph was Project Manager of the German CHAMP mission from 1994-2000, and later Project Director of the CHAMP mission exploitation phase. He was Co-Principal Investigator for the US-German GRACE (Gravity Recovery and Climate Experiment) mission 1997-2007. Today the GFZ continues this vital role in the GRACE-FO mission.

Christoph Reigber retired from the GFZ in November 2004 not because he'd grown too old to continue playing a leadership role in international geodesy, but due to German Federal Government regulations on public service retirement at 65 years of age. During his whole career Christoph advocated for, and practiced, international coordination and collaboration to further the science and applications of modern geodesy. His role in the IAG spanned from being a member of numerous Working Groups, to being President of the CSTG (International Coordination of Space Techniques for Geodesy & Geodynamics), President of the IAG's Commission 2 ("Advanced Space Technology"), Chair of the Directing Board of the IERS (International Earth Rotation & Reference Systems Service) 1995-2000, Chairman of the Governing Board of the IGS 1999-2002, and Chairman of the IAG's GGOS (Global Geodetic Observing System) pilot project 2003-2005.

Christoph also was a member of many committees, councils and working groups beyond the IAG, all of which reflect his interest in promoting space technology for the benefit of science and society. Several are worthy of mention. Christoph was a Member of the Board of Trustees of the Werner von Braun Foundation for Space Science Advancement 2002-2008; Member of the Scientific Advisory Board for the Space Research Institute of the Austrian Academy of Sciences 2008-2017; and Vice-chair and Member of the Scientific Advisory Board of the Central Asian Institute of Applied Geosciences in Bishkek, Kyrgyzstan 2011-2018.

Christoph's contributions have won him many honours and awards, which include the CNES "Médaille de Bronze" (1977), the Alexander von Humboldt Prize for Scientific Cooperation between Germany and France (1985), the NASA Group Achievement Award (Crustal Dynamics Project) (1986), Fellow of IAG (1991), ERS-1 Award of ESA (1992), AGU Fellow (1994), Honorary Doctorate (Dr.-Ing. E.h.), University Bonn (1998), the Vening Meinesz Medal of the European Geophysical Society (2002), Honorary Professorship of Wuhan University, China (2003), the DLR Werner von Braun Medal (2003), the NASA Earth Explorers Program Office GRACE Mission Award (2006), the William T. Pecora Award for the GRACE Team (2007), the State Award of the Republic of Kyrgyzstan (2008), the Grand Prix of the French Air & Space Academy (2010), Member of Academia Europaea (2014), and the William Nordberg Medal of COSPAR (2018), inclusive the renaming of asteroid 6314 to REIGBER.

In summary, *Christoph Reigber* has made an enormous contribution to the IAG, and geodesy in general, making him a most worthy recipient of the Levallois Medal. On a personal note, I have known *Christoph Reigber* since 1981, when I was awarded an Alexander von Humboldt Fellowship to undertake postdoctoral studies at DGFI. This was a life-changing experience, and I subsequently took a sabbatical at the GFZ in 1995. I am humbled by what he has achieved in his professional life, but I also treasure my personal friendship with Christoph, his wife Nunu, and their two children Astrid and Andreas. I am honoured to be asked to prepare this Laudation.

Guy Bomford Prize Lecture
Advancing the theoretical apparatus of physical geodesy

Michal Šprlák[1]

Mister President, Mister Secretary General, Ladies and Gentlemen, I am very pleased and honoured. The other day, I looked at the list of the Guy Bomford Prize awardees. Honestly, I feel like a hobbit who has just arrived in the Rivendell and there are the wise Elves all around him. I will express my gratitude at the end of this talk. Now, I would like to tell you a few words about the advancements of the theoretical apparatus of physical geodesy. This is the topic, which I have been very passionate about and also quite productive in terms of research outputs, and brought me here on this stage tonight. Vast majority of this research has been performed at the University of West Bohemia in the Czech Republic together with my colleagues *Pavel Novák* and *Martin Pitoňák*. Currently, however, I am employed at the University of Newcastle in Australia.

You certainly know that gravitational field reveals important properties of our planet and it definitely deserves to be one of the main pillars of geodesy. Enormous amount of gravitational data has been collected by various sensors in the past decades. This has mainly stimulated for various revolutionary applications in geosciences. But those who are more theoretically gifted have also been working hard. They have improved the existing concepts and have even gone way further than allowed by the available datasets. In my opinion, we have experienced a renaissance in the theoretical developments in the past few years. My colleagues and I have contributed to these advancements by solving interesting theoretical problems. For simplicity, I divided our research contributions into three categories and it is now my intention to briefly describe each of them.

The first group is about a more complete picture of the third-order gravitational tensor. I came with this idea more or less out of curiosity. No wonder that I encountered strong resistance and doubts. Fortunately, I could find papers and patents reporting actual measurements of the third-order potential derivatives that saved my initial goal. On the left-hand side (see Fig. 1), you can see the mathematical expression of the third-order gravitational tensor in the gradient and component forms. On the right-hand side, you can observe its visualisation as a cube with 27 components. Apparently, the third-order gravitational tensor is a complex mathematical object.

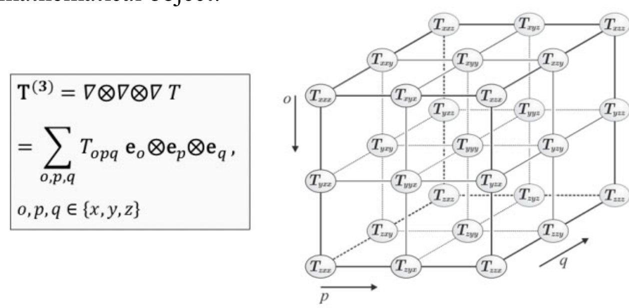

Figure 1: The third-order gravitational tensor

We discovered the secrets of this tensor by looking at its basic properties, such as symmetries of the components, and by constructing the differential operators (Šprlák and Novák 2015). We then found how the gravitational potential could be determined from the third-order tensor components by solving the spherical gravitational curvature boundary-value problem (Šprlák and Novák 2016). We continued further with harmonic analysis and even investigated what could be achieved when observing the third-order potential derivatives by a satellite (Šprlák et al. 2016). Later on, my younger colleagues dealt with more practical aspects, such as non-singular harmonic synthesis (Hamáčková et al. 2016)

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or the integral inversion of these quantities (Pitoňák et al. 2017). In this way, we collected necessary bits and pieces and built the first systematic methodology for the third-order gravitational tensor, just like it had been done decades ago, but for lower-rank gravitational tensors.

The second group of theoretical problems are those on integral transformations. An excellent example of an integral transformation is the famous Stokes integral, which every geodesist and even surveyor knows. It nicely illustrates how gravity anomalies are converted to geoid undulations. It also represents analytical solution of the third boundary-value problem. For real world applications, we directly calculate this integral or solve its inverse.

There are many quantities that we would like to transform from one to another (see Fig. 2). These are the disturbing potential on the left, and its first, second, and third-order derivatives towards right. The quantities that we integrate over are on the lower level at the reference sphere of radius R. The computed quantities are at the upper level at the radius r. Imaginary line connecting one box from the lower level with one box at the upper level could define an existing integral transformation.

Many geodesists have added lines to this schematic and so have we in a collection of seven research papers published in Journal of Geodesy. These publications are listed in the box on the left (see Fig. 2). The different colours help us to identify individual lines in the diagram and thus the related quantities. In total, we derived impressive 98 integral transformations. But we were not obsessed only with equations. We investigated spatial behaviour of the integral kernels that leads to some practical implications, such as efficient numerical calculation, the effect of the distant zones, or suitability for inverse problems. Also, almost every integral formula was implemented in a computer program and validated in a closed-loop simulation.

Finally, our effort culminated in a review paper published in Earth-Science Reviews (Novák et al. 2017). Here, we summarised mutual integral formulas among the disturbing gravitational potential, its first, second, and third-order derivatives including eventually all references from the geodetic literature. Thus, the diagram in Fig. 2 has been completed.

So far, we have silently assumed spherical geometry. Once you solve numerous tasks using this approximation, you get a little bored and the next challenging step is to consider its spheroidal equivalent. This is the third part of my talk. We use a spheroid instead of a sphere, because it more closely fits the shape and the gravitational field of our planet. On the other hand, we lose the comfort of the azimuthal symmetry. In other words, every direction is somewhat different on the spheroidal surface and we cannot simply introduce the polar coordinates that are so efficient on the sphere. In addition, spheroidal counterparts of the addition theorem and orthogonality relationships either do not exist or are defined differently from the familiar spherical case.

With the help of great findings by geodetic forefathers, we could handle these complications and expand the existing class of spheroidal integral transformations. Firstly, we formulated a mathematical model for inverting gravimetric and gradiometric measurements to the gravitational potential (Novák and Šprlák 2018). Secondly, we applied two orthogonalisation approaches to solve the spheroidal vertical and horizontal boundary-value problems (Šprlák and Tangamrongsub 2018). There are other interesting tasks to be solved, thus the spheroidal story is not over yet.

Because we addressed all three parts, it is now time to conclude. You may have seen that we have significantly extended the theoretical apparatus of physical geodesy. These advancements are not restricted to geodesy and also enhance the more general framework of the potential theory. The new mathematical formulations represent the basis for the gravitational field modelling and we have applied some of them in several applied studies. We are confident that the new complex mathematical models can be implemented and describe the reality very well. The presented work has been a part of activities within the Joint Study Group called "Integral equations of potential theory for continuation and transformation of classical and new gravitational observables" of the Inter-Commission Committee on Theory under the umbrella of the International Association of Geodesy. For the first time, I have acted as a chairman of this study group that has been a very pleasant experience in addition to deriving dozens of equations.

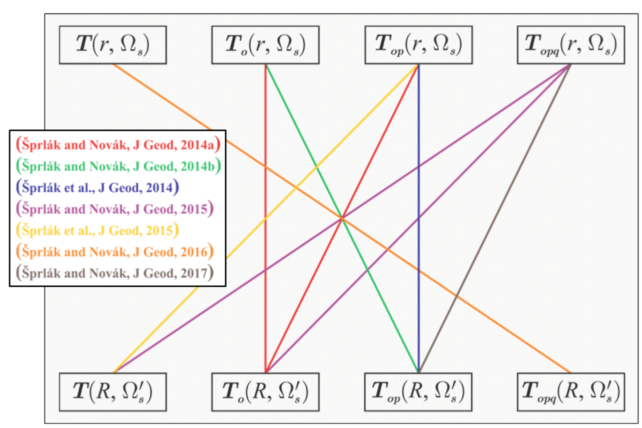

Figure 2: Schematic of the derived integral transformations

Acknowledgements

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Michal Šprlák

IAG Young Authors Award 2015
Citation for Xingxing Li

The IAG Young Authors Award 2015 is presented to Dr. *Xingxing Li* for his paper *Accuracy and reliability of multi-GNSS real-time precise positioning: GPS, GLONASS, BeiDou, and Galileo*. The work was published in the Journal of Geodesy, 2015, Volume 89, Issue 6, pp.607-635.

The lead author, Dr. *Xingxing Li*, has focused on high-precision GNSS and Geosciences' applications for more than ten years. He started his Geodesy studies at Wuhan University in 2004. In 2010, he was hired by the German Research Center for Geosciences (GFZ) as a project scientist for the project "Online-GNSS service with scalable accuracy for precise positioning and navigation". In 2015, he defended his doctoral thesis on "Real-time high rate GNSS techniques for earthquake monitoring and early warning" at Technische Universität Berlin.

He has already received several awards. In 2012, he won the ION paper Award and he won the GFZ "Friedrich-Robert-Helmert" Award in 2016. In 2017, he won the EGU Outstanding Young Scientist Award. Dr. Li has an excellent publication record with more than 30 papers in leading ISI journals of his research field during this period and in majority as first author. Currently, he is the Chair of the IAG working group "Biases in Multi-GNSS data processing" and the co-Chair of the EGU session "High-Precision GNSS Algorithms and Applications in Geosciences".

The award-winning paper presents a four-system integrated model with GPS, GLONASS, BeiDou and Galileo for real-time precise orbit determination, clock estimation and positioning. Meanwhile, an efficient multi-GNSS real-time precise positioning service system is designed and demonstrated. A rigorous multi-GNSS analysis is performed to achieve the best possible consistency by processing the observations from different GNSS together in one common parameter estimation procedure. For satellite orbit, the overlap (two adjacent three-day solutions) RMS values of estimated Galileo orbits are 2.1, 3.7 and 7.8 cm, respectively in radial, cross and along components. The corresponding overlap RMS values for BeiDou IGSO satellites are 2.5, 3.3, and 4.4 cm in the three components, respectively. The RMS values of BeiDou MEO satellites are 3.4, 4.3 and 11.3 cm in the radial, cross, and along directions, respectively.

The GEO satellites have comparable performance compared with IGSO and MEO satellites in the radial and cross directions, but the accuracy in the along component decreases to about 1 m due to the rather weak geometry. For satellite clock, the RMS values of clock differences between the real-time and batch-processed solutions for GPS satellites are about 0.10 ns, while the RMS values of BeiDou, Galileo and GLONASS satellites are 0.13, 0.13 and 0.14 ns, respectively. Both satellite orbits and clocks can achieve an accuracy of cm level in real time. It is worth noting that the errors of orbits and clocks can be compensated by each other when they are used together at user end. For precise point positioning (PPP), it can be used to validate the capability of real-time precise positioning service based on the predicted orbits and real-time estimated clocks.

The multi-GNSS PPP shows faster convergence and higher accuracy in all three components than single-system PPP. After adding BeiDou, Galileo and GLONASS systems to the standard GPS-only processing, the convergence time is decreased by 70 % and the positioning accuracy is improved by 25 %. The real-time positioning capabilities of the combined systems under different elevation cutoffs is different. Its positioning accuracy hardly decreases and an accuracy of several centimeters is still achievable in horizontal components even with a 40° elevation cutoff. At 30° and 40° elevation cutoffs, the availability rates of GPS-only solutions drop dramatically to only around 70 and 40%, respectively. However, multi-GNSS PPP shows excellent results.

In a word, the fusion of multiple GNSS significantly increases the number of observed satellites, optimizes the spatial observation geometry at a site and improves convergence, accuracy, continuity and reliability of positioning solutions. Moreover, the performance of multi-GNSS integration at high elevation cutoffs will significantly increase its applications in constrained environments, such as in urban canyons, open pits and mountainous areas.

IAG Young Authors Award 2016
Citation for Olga Didova

The IAG Young Author Award 2016 is given to *Olga Didova* for her paper *An approach for estimating time-variable rates from geodetic time series*, which has been published in the Journal of Geodesy (2016) 90:1207-1221. The paper is co-authored by *Brian Gunter*, *Riccardo Riva*, *Roland Klees*, and *Lutz Roese-Koerner* representing 3 different scientific institutions.

The original article considers the problem of estimating trends in mass loss over Antarctica from GRACE and GPS time series in the presence of inter-annual and seasonal variability. The traditional approach parameterizes the time series using a bias, trend, and harmonic constituents, which are considered as being deterministic. The main weakness of this approach is that the distinct components of mass loss (as those of many other geophysical processes) are not deterministic, but fluctuate in time around some reference values.

The idea to model them stochastically using a state space model and estimating the state parameters using a Kalman filter was introduced to the geodetic community in a paper by Davis et al (2012), though state space analysis is a well-established methodology for treating a wide range of problems in the analysis of econometric time series as documented in the excellent books by Harvey (1989) and Durbin and Koopman (2012). Davis et al (2012) assumed that the parameters, which determine the stochastic movements of the state variables ("hyperparameters"), are known. Moreover, little is known in econometric literature about the robust estimation of hyperparameters, which is a non-convex optimization problem.

In her paper, Olga considers the hyperparameters as unknowns and estimates them using Maximum Likelihood. The optimization problem is solved using a gradient-based local solver, which can deal with non-convex problems. To increase the probability of finding the global minimum, Olga suggests to define a random set of uniformly distributed starting values and selects the starting values that provides a solution which has the smallest log likelihood objective function. To improve the chance of finding the global minimum, Olga suggests several measures to limit the parameter search space. Moreover, she introduces inequality constraints on some of the hyperparameters, and suggests a method, involving among others a likelihood ratio test and an algorithm for determining the degrees of freedom for this test, to verify whether the constraints are supported by the data.

The suggested methodology is applied to the analysis of real GRACE and GPS time series, both representing vertical deformations due to elastic and visco-elastic responses of the solid Earth to surface loading. The data analysis reveals that compared to the classical deterministic model using least-squares, the proposed methodology provides more reliable trend estimates, because it accounts for any long-term evolution in the time series and avoids any contamination from seasonal variability.

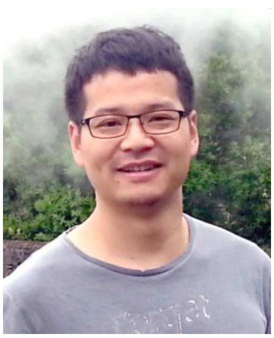
The proposed methodology may become a standard tool in time series analysis of geodetic data, in particular when long time series comprising years of data are involved.

Olga Didova studied Geodesy and Geoinformation at the University of Bonn, Germany. She received her Bachelor of Science in 2009 and her Master of Science in 2011 under supervision of *Karl Heinz Ilk* and *Juergen Kusche*, respectively. Between 2012 and 2016, she was a PhD candidate at Delft University of Technology in the Department of Geoscience and Remote Sensing working on "Separating GIA and ice mass change signals in Antarctica using satellite data". She will defend her PhD thesis at Delft University of Technology in fall 2017. Since March 2017, she is a Postdoctoral Fellow at the University of Bonn and involved in the assimilation of remote sensing data in a hydrological model.

References:

JL Davis, BP Wernicke, ME Tamisiea (2012), On seasonal signals in geodetic time series. J Geophys Res 117(B01403).
AC Harvey (1989), Forecasting, structural time series models and the Kalman filter. Cambridge University Press, Cambridge.
J Durbin, SJ Koopman (2012), Time series analysis by state space methods. Oxford University Press, Oxford.

Young Authors Award 2017
Citation for Minghui Xu



The IAG Young Authors Award 2017 is presented to Dr. Minghui Xu for his paper *The impacts of source structure on geodetic parameters demonstrated by the radio source 3C371*. The work was published in the Journal of Geodesy, 2017, Volume 91, pp.767-781.

The leading author, Dr. *Minghui Xu*, has focused on high-precision very long baseline interferomery (VLBI) studies for ten years. He started his Geodesy studies in Shanghai Astronomical Observatory (SHAO) in 2009. In 2013, he got the German DAAD scholarship to join the German Research Center for Geosciences (GFZ) VLBI group for his PhD. He defensed his doctoral thesis on *Determining the acceleration of Solar System's Barycenter by VLBI* at SHAO in 2015. He was awarded as a Mercator Fellow in Germany in 2017. Currently, he is the research fellow in Aalto University Metsahovi Observtory and is working on mitigating source structure effects on broadband VLBI (VGOS) observations in order to achieve the goal of VGOS, the mm accuracy of station positions on global scales.

The award-winning paper investigates closure quantities measured by very-long-baseline interferometry (VLBI) observations that are independent of instrumental and propagation instabilities and antenna gain factors, but are sensitive to source structure. A new method is proposed to calculate a structure index based on the median values of closure quantities rather than the brightness distribution of a source. The results are comparable to structure indices based on imaging observations at other epochs and demonstrate the flexibility of deriving structure indices from exactly the same observations as used for geodetic analysis and without imaging analysis.

A three-component model for the structure of source 3C371 is developed by model-fitting closure phases. It provides a real case of tracing how the structure effect identified by closure phases in the same observations as the delay observables affects the geodetic analysis, and investigating which geodetic parameters are corrupted to what extent by the structure effect. Using the resulting structure correction based on the three-component model of source 3C371, two solutions, with and without correcting the structure effect, are made. With corrections, the overall rms of this source is reduced by 1 ps, and the impacts of the structure effect introduced by this single source are up to 1.4 mm on station positions and up to 4.4 microarcseconds on Earth orientation parameters. This study is considered as a starting point for handling the source structure effect on geodetic VLBI from geodetic sessions themselves.

Young Authors Award 2018
Citation for Athina Peidou

Granted for the article*: On the feasibility of using satellite gravity observations for detecting large-scale solid mass transfer events*, Journal of Geodesy, Vol. 92, pages 517-528 by *Athina Peidou*, *Georgia Fotopoulos* and *Spiros Pagiatakis*. The focus of the paper is to assess the feasibility of using dedicated satellite gravity missions (specifically GRACE) to detect large-scale solid mass transfer events (e.g. landslides).

Dr. *Athina Peidou* holds an undergraduate degree from the School of Rural and Surveying Engineering at Aristotle University of Thessaloniki graduating at the top of her class. She pursued Master's studies in the Geophysics and Geodesy Lab of the Department of Geological Sciences and Geological Engineering at Queen's University, Kingston, Canada. For her PhD studies, Athina joined Prof *Spiros Pagiatakis's* Space Geodesy Lab in the Department of Earth and Space Science and Engineering at York University, Toronto, Canada. She defended her doctoral thesis in 2020 which was awarded with Canada's General Governor's Gold Medal. Recently, she joined NASA's Jet Propulsion Laboratory as a postdoctoral research fellow to work on GRACE and GRACE-FO missions.

The main objective of the award-winning paper was to determine the feasibility of detecting landslides and earthquakes using models derived from GRACE mission measurements. This was assessed through a sensitivity analysis of GRACE- gravity field solutions in conjunction with simulated case studies of large-scale solid mass transfers. The simulations focused on determining the effect of various-scale geohazards on the gravity field as measured by GRACE, and this was achieved by means of 3-D forward modelling and 2-D wavelet multi-resolution analysis. Real events studied include catchment-scale events such as the Heart Mountain Landslide (50km x 70km) and the Tohoku earthquake triggered submarine landslide (40km x 20km) as well as regional scale events such as the Agulhas slump (750km x 106 km) and the Grand Banks slide (1000km x 25km). Results indicate the spatial extent (and volume) of mass transfer events that can be detected using GRACE measurements. Additionally, the study proceeds with sensitivity analysis of the impact of the altitude of the satellite on the resolvability of a mass transfer, assuming an inherent noise level of approximately 30 microgals (this includes satellite noise and aliasing effects). Overall, this study improves our understanding on mass movement processes and their direct impact on the gravity field as mapped by the dedicated missions.

Due to limited information on oceanic environments, most submarine landslides remain unknown while the detrimental effects of landslides on societies are often documented in the news. With satellite gravity measurements being continuously available, detection of submarine events could be feasible; therefore this research constitutes an important contribution towards detecting the Earth's dynamic processes in submarine environments.

Report of the IAG Secretary General

Hermann Drewes

According to the IAG Bylaws, the Secretary General serves as the secretary of the General Assembly, the Scientific Assembly, the Council, the Executive Committee and the Bureau. He arranges for meetings of these bodies, distributes promptly the agenda, and prepares and distributes the minutes of all their meetings. He acts as the Director of the IAG Office and manages the affairs of the Association including the finances. He continuously attends to the IAG correspondence, preserves the records and circulates all appropriate information related to the Association. He has to prepare the reports of the Association's activities and to perform other duties as may be assigned by the Bureau, the Council and the Executive Committee.

1. Administrative work

Administrative works with the greatest efforts in the period 2015-2019 were the preparation and execution of the joint IAG/IASPEI Scientific Assembly 2017 and the IUGG General Assembly 2019. Other major actions include the edition of the Geodesist's Handbook 2016 and the IAG Reports Vol. 40 and Vol. 41 (Travaux de l'AIG 2015–2017 and 2015–2019), the organisation of eight meetings of the IAG Executive Committee, and the sponsoring of 44 IAG scientific meetings. The management of financial affairs applies to all IAG accountings, including the Journal of Geodesy and IAG Symposia Series, three IUGG sponsored Projects and Symposia, and the handling of the individual IAG membership. 61 travel awards were granted to young scientists for participation in IAG symposia, and 72 awards for assisting the IUGG General Assembly 2019.

1.1 Scientific Assembly

The IAG Scientific Assembly was organised together with the International Association of Seismology and Physics of the Earth's Interior (IASPEI) in Kobe, Japan, July 30 to August 4, 2017. The full assembly reports are published at https://www.iag-aig.org/doc/5ceea88fa6e85.pdf and at http://www.iugg.org/publications/ejournals/IUGGej1712.pdf. 1107 attendees from 65 countries registered and presented 1119 lectures and posters in 43 symposia, 9 of these as joint IAG-IASPEI Symposia. The symposium proceedings were published in the IAG Symposia Series, Vol. 149.

1.2 General Assembly

The IAG held its General Assembly, as usual, together with the IUGG General Assembly in Montreal, Canada, July 8 to 18, 2019. The general report is published at http://www.iugg.org/publications/ejournals/IUGGej1909.pdf and the IAG part in the present volume. 3952 participants registered, 437 of them with IAG priority. There were 234 Symposia and 18 Workshops with 4580 presentations, 469 in IAG Symposia. IAG organised one Union Symposium, 7 Joint Symposia with other associations, 6 IAG Symposia, and 20 business meetings. In addition, IAG co-sponsored 8 Union Symposia and 15 Joint Symposia. *Kosuke Heki* gave a Union lecture on behalf of the IAG. 72 travel awards for IAG participants were granted from IUGG and IAG.

1.3 Council

The IAG Council consists of the delegates appointed by the Adhering Bodies of the IUGG member countries and is responsible for governance, strategic policy and direction of the IAG. The Secretary General continuously informs them on actual IAG activities and events. The Council meetings at the Scientific Assembly 2017 in Kobe, Japan, and the IUGG General Assembly 2019 in Montreal, Canada, were prepared and minutes were published (the latter in this volume). The national delegates' list is regularly updated in contact with the IUGG Secretariat.

1.4 IAG Executive Committee (EC)

The duties of the Executive Committee are to further the objectives of the IAG through effective coordination and the formulation of general policies. Eight EC meetings were organised during the legislative period 2015 to 2019 (Prague, Czech Republic, July 2015; San Francisco, USA, December 2015; Potsdam, Germany, April 2016; Vienna, Austria, April 2017 and April 2018; Kobe, Japan, July 2017; Washington, USA, December 2018; and Montreal, Canada, July 2019). The minutes were distributed, and meeting summaries were published in the IAG Newsletter, the Journal of Geodesy (the latest in this volume) and on the IAG Websites (https://office.iag-aig.org/meeting-summaries).

1.5 IAG Bureau

The IAG Bureau consists of the IAG President, the Vice President and the Secretary General. It meets normally before each EC meeting and holds regular teleconferences to administer the day-to-day affairs. The President and the Secretary General participated in the meetings of the IUGG Executive Committee and represented the IAG at international meetings of allied scientific bodies.

1.6 IAG Office

The IAG Office was located from 2007 to 2019 at the Deutsches Geodätisches Forschungsinstitut, Technische Universität München, Germany. A Website for internal IAG affairs was maintained at https://iag.dgfi.tum.de.

1.7 Publications

The IAG Secretary General manages the financial affairs of the Journal of Geodesy and IAG Symposia Series. The following volumes of the latter were published 2015-2019:

- 142: VIII Hotine-Marussi Symposium Rome 2013;
- 143: IAG Scientific Assembly, Potsdam 2013;
- 144: 3rd IGFS Symposium, Shanghai 2014;
- 145: GENAH Symposium, Matsushima 2014;
- 146: REFAG Symposium, Luxembourg 2014;
- 147: IAG General Assembly, Prague 2015;
- 148: Gravity, Geoid, Height Systems, Thessaloniki 2016;
- 149: IAG Scientific Assembly, Kobe 2017.

The biannual IAG Reports are published in the Travaux de l'AIG 2017 (Vol. 40) and 2019 (Vol. 41) and may be found at https://iag.dgfi.tum.de. Annual IAG reports are published in the IUGG Annual Reports and Yearbooks.

1.8 Individual Membership

The IAG has at present about 180 paying individual members and 40 free student members. The membership fee (USD 50 per year or USD 150 per 4 years) is collected by credit cards or bank transfer. The membership list is regularly updated in cooperation with the Communication and Outreach Branch for distributing the IAG Newsletter. The actual lists are provided to the Organizing Committees of IAG Symposia in order to reduce the registration fee for IAG members according to the IAG Bylaws.

1.9 IAG Awards

There are three IAG Awards for meritorious work of IAG associates, normally presented at the IAG Scientific and General Assemblies (see https://www.iag-aig.org/awards):

- Levallois Medal for distinguished service to the IAG and/or to the science of geodesy in general. In 2019, it was granted to *Christoph Reigber*, Germany.
- Guy Bomford Prize for outstanding contributions of a young scientist to geodetic studies. In 2019, it was granted to *Michal Šprlák*, Australia.
- Young Authors Awards for the best publications in the Journal of Geodesy. For 2017 it was granted to *Minghui Xu*, China, and for 2018 to *Athina Peidou*, Canada.

2. IAG Symposia, Workshops and Schools

Important meetings of the IAG components and meetings sponsored by the IAG from July 2015 to June 2019 were:

- International DORIS Service (IDS) Analysis Working Group Meeting, Greenbelt, MD, USA, 15-16 Oct. 2015.
- International Laser Ranging Service (ILRS) Analysis Working Group Meeting, Matera, Italy, 24 Oct. 2015.
- International Laser Ranging Service (ILRS) Technical Workshop 2015, Matera, Italy, 26-30 Oct. 2015.
- Latin American Reference System (SIRGAS) Symposium, Santo Domingo, Dominican Republic, 18-20 Nov. 2015.
- 9th International Symposium on Mobile Mapping Technology (MMT2015), Sydney, Australia, 9-11 Dec. 2015.
- IGS Workshop, Sydney, Australia, Feb. 15-19, 2016;
- 9th IVS General Meeting, Ekudeni, Johannesburg, South Africa, March 13-17, 2016;
- 3rd Joint Symposium on Deformation Monitoring, Vienna, Austria, March 30 – April 1, 2016;
- 4th IAG Symposium "Terrestrial gravimetry: Static and mobile measurements", Saint Petersburg, Russia, April 12-15, 2016;
- European Reference Frame Symposium (EUREF 2016), San Sebastian, Spain, May, 25-27, 2016;
- 18th Geodynamics and Earth Tide Symposium 2016, Trieste, Italy, June 5-9, 2016;
- IAU/IAG/IERS Symposium "Geodesy, Astronomy and Geophysics in Earth Rotation (GAGER2016)", Wuhan, Hubei, China, July 18-23, 2016;

- International Symposium on Geodesy and Geodynamics (ISGG2016), Tianjin, China, July 22-26, 2016;
- 1st International Conference on GNSS+ (ICG+2016), Shanghai, China, July 27-30, 2016;
- IAG Commission 4 “Positioning and Applications” Symposium, Wroclaw, Poland, Sep. 4-7, 2016;
- 18th General Assembly of WEGENER “Understanding Earth deformation at plate boundaries”, Ponta Delgada, Azores, Portugal, Sep. 12-15, 2016;
- 1st Joint Commission 2 and IGFS Meeting, International Symposium on Gravity, Geoid and Height Systems 2016 (GGHS2016), Thessaloniki, Greece, Sep. 19-23, 2016;
- First International Workshop on VLBI Observations of Near-field Targets, Bonn, Germany, October 5-6, 2016;
- 20th International Workshop on Laser Ranging, Potsdam, Germany, Oct. 9-14, 2016;
- GGOS Days, Cambridge, MA, USA, Oct. 24-28, 2016;
- IDS Workshop, La Rochelle, France, Oct. 31 – Nov. 1, 2016;
- Reference Frame for South and Central America Symposium (SIRGAS2016), Quito, Ecuador, Nov. 16-18, 2016;
- 1st International Symposium - Applied Geomatics and Geospatial Solutions, Rosario, Argentina, April 3-7, 2017;
- 9th IVS Technical Operations Workshop, Westford, MA, USA, April 30 – May 4, 2017;
- EUREF 2017 Symposium, Wroclaw, Poland, May 17-19, 2017;
- DORIS Analysis Working Group Meeting, London, UK, May 22-24, 2017;
- 21st Meeting of the Consultative Committee for Time and Frequency, Sèvres, France, June 6-9, 2017;
- 1st IUGG Symposium on Planetary Science, Berlin, Germany, July 3-5, 2017;
- IGS Workshop 2017, University of Paris-Diderot, France, July 3-7, 2017;
- IAG/GGOS/IERS Unified Analysis Workshop, Paris-Diderot, France, July 10-12, 2017;
- 2017 GNSS Tsunami Early Warning System Workshop, Sendai, Japan, July 25-27, 2017;
- IAG and IASPEI Joint Scientific Assembly, Kobe, Japan, July 30 – Aug. 4, 2017.
- Asia-Pacific Space Geodynamics Symposium, Shanghai, China, Aug. 15-18, 2017;
- Workshop on Glacial Isostatic Adjustment and Elastic Deformation, Reykjavik, Iceland, Sep. 5-7, 2017;
- 3rd COSPAR Symposium “Small Satellites for Space Research”, Jesu, South Korea, Sep. 18-19, 2017;
- IAG Workshop “Satellite Geodesy for Climate Studies”, Bonn, Germany, Sep. 19-21, 2017;
- Journées des Systèmes de Référence et de la Rotation Terrestre, Paris, France, Sep. 25-27, 2017;
- International Review Workshop on Satellite Altimetry Cal/Val Activities and Applications, Chania, Greece, April 23-26, 2018;
- EUREF Symposium 2018, Amsterdam, Netherlands, May 30 – June 01, 2018;
- 10th IVS General Meeting, Longyearbyen, Spitsbergen, Norway, June 3-8, 2018;
- 1st Workshop of the International Geodynamics and Earth Tide Service (IGETS), Potsdam, Germany, June 18-20, 2018;
- IX Hotine-Marussi Symposium on Mathematical Geodesy, Rome, Italy, June 18-22, 2018;
- 42nd COSPAR Scientific Assembly incl. IAG Commission 1 Symposium, July 14-22, 2018;
- IAG Commission 1 Symposium Reference Frames for Applications in Geosciences (REFAG2018), Pasadena, CA, USA, July 15-21, 2018;
- 8th UN-GGIM Session, New York, USA, Aug. 1-3, 2018;
- XXXth General Assembly of the IAU, Vienna, Austria; Aug. 20-31, 2018;
- 19th General Assembly of WEGENER, Grenoble, France, Sep. 10-13, 2018;
- Gravity, Geoid and Height Systems (GGHS 2) Symposium, Copenhagen, Denmark, Sep. 17-21, 2018;
- International DORIS Service (IDS) Workshop, Ponta Delgada, Azores Portugal, Sep. 24-26, 2018;
- GGOS Days 2018, Tsukuba, Japan, October 2-4, 2018;
- SIRGAS Symposium 2018, Aguascalientes, Mexico, Oct. 9-12, 2018;
- SIRGAS Workshop on Vertical Reference System, Mexico, Oct. 15-17, 2018;
- IGS 2018 Workshop, Wuhan, China, Oct. 29 – Nov. 2, 2018;
- International Workshop on GNSS Ionosphere (IWGI2018), Shanghai, China, Nov. 4-6, 2018;
- 21st Workshop on Laser Ranging, Canberra, Australia, Nov. 5-9, 2018.
- 24th Meeting of the European VLBI Group for Geodesy and Astronomy (EVGA) and 18th IVS Analysis Workshop, Las Palmas, Gran Canaria, Spain, March 14-20, 2019;
- IGS 2019 Analysis Workshop, Potsdam, Germany, April 15-17, 2019;
- 10th IVS Technical Operations Workshop, Westford, MA, USA, May 5-9, 2018;
- 4th Joint International Symposium on Deformation Monitoring, Athens, Greece, May 15-17, 2019;
- EUREF 2019 Symposium, Tallinn, Estonia, May 22-24, 2019.

The following IAG Schools were sponsored:

- VII SIRGAS School on Reference Systems, Santo Domingo, Dominican Republic, 16-17 Nov. 2015.
- 2nd IVS Training School on VLBI for Geodesy and Astrometry, Hartebeesthoek, South Africa, March 9 – 12, 2016;
- Geoid School, Ulaanbaatar, Mongolia, June 6-10, 2016;
- SIRGAS School on Vertical Reference Systems, Quito, Ecuador, Nov. 21-25, 2016;
- 3rd IVS Training School on VLBI for Geodesy and Astrometry, Las Palmas, Gran Canaria, Spain, March 14-20, 2019.

3. Finances

The financial report includes the result 2015-2018 (Table 1), the budget 2019-2023 (Table 2) and the report of the Audit Committee (Appendix A).

Table 1: Financial Report 2015-2018

	Result 2015 - 2018 in EUR				
	Expenditures			**Receipts**	
11.2	Administration Equipment	1.381,71	15	IUGG Allocation	110.326,00
11.5	Administration Travel	11.973,25	1	Membership Fee	17.619,93
11.6	Administration Representation	9.129,02	2	Other Grants	9.202,04
12.2	Publications	2.992,50	3.2	Journal of Geodesy	20.000,00
13.1	Assemblies, Organisation	9.634,20	4.1	IAG Fund	173,04
14.2	Symposia, Travel Awards	58.892,35	4.2	Geoid School	34,33
16.2	Prizes, Young Authors Awards	4.070,00			
18.6	Credit Card Service	406,13			
19	**Total Expenditures**	**98.479,16**	**6**	**Total Receipts**	157.355,34
	Surplus	58.876,18			
	Total	**157.355,34**		**Total**	**157.355,34**

	Balance 2018 in EUR		
Assets		**Liabilities**	
Staatoberkasse/TUM 31.12.2014	135.726,15	Net Capital 31.12.2018	194.602,33
Deficit 2015	-4.941,21	Surplus / Deficit	0,00
Surplus 2016	23.344,64		
Surplus 2017	27.731,23		
Surplus 2018	12.741,52		
Total	**194.602,33**	**Total**	**194.602,33**

Net Capital 2018 in EUR	
Open 1.1.2015	135.726,15
Surplus	58.876,18
Total	**194.602,33**

Table 2: Budget 2019-2022

	Budget for the period 1.1.2019 - 31.12.2022 in EUR				
	Expenditures			**Receipts**	
11.2	Administration, Equipment	3.000	15	IUGG Allocation	80.000
11.5	Administration, Travel	25.000	1	Membership Fee	15.000
11.6	Administration, Representation	10.000	2	Other Grants	4.000
12.1	Publications, Outreach	7.000	3	Sales of Publications	
12.2	Publications, IAG Symposia Series	40.000	3.1	IAG Symposia Series	0
13.1	Assemblies, Organization	20.000	3.2	Journal of Geodesy	20.000
13.2	Assemblies, Travel	10.000	4	Miscellaneous	
14.2	Symposia, Travel Awards	60.000	4.1	IAG Fund	1.000
16.2	Prizes, Young Authors Awards	4.000	4.2	Geoid School Lecture Notes	0
18.6	Credit Card Service	1.000			
19	**Total Expenditures**	**180.000**	**6**	**Total Receipts**	**120.000**
				Deficit	60.000
	Total	**180.000**		**Total**	**180.000**

	Net Capital 2022 in EUR		
Balance 31.12.2022	135.000	Open 1.1.2019	195.000
		Deficit	-60.000
Total	**135.000**	**Total**	**135.000**

Appendix A

IAG Audit Committee Report

Committee members appointed by the IAG Council:
Denizar Blitzkow, Jonas Agren, Matt Amos

1. **The Audit Committee performed the following functions:**

1.1 Noted that the accounts had previously been reviewed by the Financial Department of the Technical University of Munich (TUM). The account is in Euros.
1.2 Examined the receipts and bank statements for the period 2015 – 2018. Checked the balance reports presented by the Secretary General, Hermann Drewes.
1.3 Examined expenditure to ensure conformity with the 2015 – 2018 budget as approved by the General Assembly in Melbourne, 2011.
1.4 Examined the budget proposed for the period 2019 – 2023.

2. **The Audit Committee makes the following comments on the IAG accounts:**

2.1 The accounts were well presented and the expenditures supported by receipts and bank statements.
2.2 During this period, the IAG made an unplanned surplus of €58,876.00 in contrast to the €50,000 deficit that was forecast. The variance of €108,876.18 is large considering the total turnover was €255,834.50.
2.3 The 2015-2018 surplus increases the IAG reserve from €135.726,00 to €194.602,00.
2.4 The budget for the next period (2014 – 2023) forecasts a deficit of €60,000.

3. **The Audit Committee makes the following recommendations:**

3.1 The budget is appropriate and the forecast deficit is prudent to reduce the balance of the IAG reserve.
3.2 The Committee recommends that the proposed budget is approved.

4. **On behalf of the IAG Council the Committee makes the following acknowledgements:**

4.1 Hermann Drewes for his efficient administration and management of IAG Office.
4.2 The Financial Department of TUM for the support and checking to the accounts.

The audit committee wishes Markku Poutanen, the new Secretary General, a successful administration.

Montreal, July 16, 2019.

Denizar Blitzkow Jonas Agren Matt Amos

Fig. 1: IAG Executive Committee Meeting, Potsdam, 4 April 2016

Fig. 2: Auditorium at the Joint IAG/IASPEI Scientific Assembly, Kobe 2017

Minutes of the IAG Council Session at the IAG-IASPEI Scientific Assembly 2017

Hermann Drewes (Secretary General) · **Robert Heinkelmann** (minute taker)

Place: Kobe International Conference Center, Room 401
Time: July 31, 18:00-20:00

Agenda

18:00 Welcome and adoption of agenda
18:05 Organizational issues of the Scientific Assembly 2017
18:20 Scientific program breakdown
18:35 Mid-term Report on IAG activities 2015-2017
18:50 IAG Strategy Document and international activities
19:30 Revision of IAG Statutes and Bylaws
19:45 Any other business
20:00 Adjourn

Participants

IAG National Delegates (*representatives)**:** Australia (*Chris Rizos), Austria (Johannes Böhm), China (Yamin Dang, *Shuanggen Yin), Czech Republic (Pavel Novak), Finland (Markku Poutanen), France (*Marie-Francoise Lalancette), Germany (Jürgen Müller), Greece (*George Vergos), India (Virendra M. Tiwari), Israel (Gilad Even-Tzur), Italy (Mattia Crespi), Japan (Kosuke Heki), New Zealand (Matt Amos), Poland (Aleksander Brzezinski), Sweden (*Martin Lidberg), Switzerland (*Alain Geiger), Turkey (Osman Atila Akabali), USA (*Jeffrey Freymueller)

IAG Executive Committee Members and Guests: Harald Schuh (IAG President), Zuheir Altamimi (IAG Vice President), Hermann Drewes (IAG Secretary General), Robert Heinkelmann (guest, minute taker)

Minutes

1. Welcome and adoption of agenda
The IAG Council Meeting 2017 took place on 31 July 2017, at the Kobe International Conference Center, in Kobe, Japan, on the occasion of the IAG-IASPEI Scientific Assembly 2017. The agenda was distributed previously by email and was unanimously adopted. *H. Schuh*, the President of the IAG, welcomed the participants of the IAG Council Meeting.

2. Organisational issues of the Scientific Assembly 2017
H. Drewes, the IAG Secretary General, welcomed the participants and mentioned that most organisational issues were already presented during the Opening Ceremony. He explained that the poster sessions are organized in another building (Chamber of Commerce and Industry) on the other side of the street.

3. Scientific programme breakdown
H. Drewes noted that this topic was already covered during the Opening Ceremony.

4. Mid-term Report on IAG activities 2015-2017
H. Drewes mentioned that the mid-term reports on IAG Activities 2015-2017 (Travaux) can be found on the IAG office website under IAG Publications, Reports). Further comments from the Council Members are very much appreciated. Printed versions of the final Travaux can be received on request.

5. IAG Strategy Document and international activities
H. Schuh gave a presentation about, international activities, IUGG issues, and the IAG Strategy Document. *He* reported about a discussion on IUGG membership, the IUGG governance, news in the IUGG structure and the Statutes and By-Laws, IUGG within ICSU and other recent IUGG

activities. Further, he reported about the IAG Strategy Document, which was prepared by *G. Beutler*. The document says that the basic structure of IAG incl. the four commissions, the ICCT and GGOS should remain the same. In addition, it says that Inter-Commission Committees (ICCs; e.g., under two or more Commissions) and Projects (e.g., under one Commission; also lasting longer than 4 years) could be established. Suggestions for topics should come from the geodetic scientists. *H. Schuh* further discussed the visions and ideas for ICCs, which were identified. He noted that Planetary Geodesy should be covered by the newly established IUGG Union Commission on Planetary Sciences (UCPS) and not by IAG.

J. Müller noted that there could be more information and ideas about how to implement the Strategy Document (e.g., how to attract early-career scientists; ranking the visions). *He* suggested incl. an early-career scientist to the IAG EC who reaches out to interested early-career scientists.

A. Geiger noted the importance of including Marine Geodesy as an Option (#4) for an ICC, and possibly later for an IAG-IAPSO Inter-Association Activity, in the Strategy Document.

H. Drewes asked the IAG Council to give further comments on the IAG Strategy Document after this meeting.

H. Schuh concluded that the IAG Strategy Document will be finalized in the next months, endorsed by the EC in 2017, and approved by the Council during the IUGG General Assembly 2019 in Montreal, Canada, at the latest. The implementation of the Strategy Document should start as soon as possible. He noted that one or two Members at Large could be added to the EC in order to improve the geographical balance, however, it would be preferred getting more nominations for IAG officers from the countries instead of increasing the number of EC members.

6. Revision of IAG Statutes and Bylaws

C. Rizos, Chair of the Cassinis Committee, presented his report on the revision of the IAG Statutes and Bylaws. *He* reported about the structure and tasks of the committee and explained the working procedure of the committee from getting ideas (e.g., from the Strategy Document) and proposals (e.g., from the Chinese National Committee) for changes until having the final revisions of the Statutes and Bylaws ready.

H. Drewes explained the difference between Statutes (general law) and the Bylaws (explanatory notes). *H. Schuh* noted that sometimes it might be better (e.g., when it comes to awards) adding an amendment instead if changing the Statutes and Bylaws itself.

7. Any other business

H. Drewes explained that the reason for not giving a reduction of 10% to the IAG individual members on the registration fee for the IAG-IASPEI Scientific Assembly was the fact that it is a joint assembly. However, all IAG members who attended the IAG-IASPEI Scientific Assembly will get free extension of their IAG membership by one year.

8. Adjourn

H. Schuh thanked the participants for their contributions and closed the session at 20:00.

Minutes of the IAG Council Sessions at the General Assembly 2019 (session 1)

Hermann Drewes (Secretary General) · **Franz Kuglitsch** (Assistant Secretary General) · **Robert Heinkelmann** (minute taker)

Place: Palais des Congrès, Montreal, Canada, Room 513C
Time: 10 July 2019, 08:30-10:00

Agenda

1. Welcome and adoption of the agenda
2. IUGG2019 organisational issues
3. Agenda of the Opening and Closing Sessions
4. Information on IAG Awards
5. Proposal of the IAG Budget 2019 – 2022
6. Appointment of the Audit Committee
7. Appointment of the Resolutions Committee
8. Review of the 2019 election process and results
9. Review of IAG Statutes and Bylaws
10. IAG Strategy Document
11. Status of Journal of Geodesy and IAG Symposia Series
12. Status of IAG Reports
13. IAG Scientific Assembly 2021
14. Any other business (all)

Adjourn

Participants

IAG National Delegates: Austria (Johannes Böhm), Brazil (Gabriel do Nascimento Guimaraes), China-Taipei (Ming Yang), Czech Republic (Pavel Novak), Denmark (Niels Andersen), Estonia (Artu Ellmann), Finland (Jyri Näränen), France (Marie-Francoise Lalancette), Germany (Jürgen Müller), Greece (Dimitrios Tsoulis), Hungary (Jozsef Adam), Italy (Mattia Crespi), Rep. of Korea (Jungho Cho), New Zealand (Matt Amos), Poland (Pawel Wielgosz), Spain (Marcelino Valdez Perez de Vargas), Sweden (Jonas Agren), Switzerland (Elmar Brockmann), Thailand (Chakorn Boonphakdee), UK (Peter Clarke), USA (Jeffrey Freymueller)

IAG Executive Committee Members: Harald Schuh (IAG President), Zuheir Altamimi (IAG Vice President), Hermann Drewes (IAG Secretary General), Richard Gross (GGOS Chair), Axel Nothnagel (Representative of the IAG Services), Roland Pail (President of IAG Commission 2), Chris Rizos (IAG Immediate Past President)

Guests: Denizar Blitzkow, Robert Heinkelmann (minute taker), Benjamin Männel, Markku Poutanen (IAG Secretary General 2019-2023)

Minutes

1. Welcome and adoption of agenda

The first session of the IAG Council Meeting 2019 took place on 10 July 2019, at the Palais des Congrès, Montreal, Canada, on the occasion of the IUGG General Assembly 2019. *H. Schuh*, the President of the IAG, welcomed the participants of the IAG Council Meeting. The agenda was distributed previously by e-mail, was unanimously adopted.

2. IUGG2019 organisational issues

H. Drewes, the IAG Secretary General, summarized the organizational issues of IUGG. He reported about (i) IAG's involvement in the science program (IAG Symposia, Joint-Symposia, poster sessions) compared to previous IUGG General Assemblies and compared to other Associations, (ii) IAG Business Meetings, (iii) IAG/IUGG ceremonies and social events, and (iv) IUGG/IAG Travel Grants (IAG offered grants of around CAD 40,000).

3. Agenda of the Opening and Closing Sessions

H. Drewes presented and discussed the agendas of the Opening and Closing Sessions.

4. Information on IAG Awards (Levallois Medal, Guy Bomford Prize, Young Authors Awards)

H. Drewes presented the IAG awardees 2019. The corresponding rules (https://www.iag-aig.org/statutes-and-by-laws) describe the procedures of nominations and decision-making. The Levallois Medal 2019 was awarded to *C. Reigber* (Germany), the Guy Bomford Prize 2019 to *M. Sprlak* (Australia), and the Young Authors Awards 2017 and 2018, respectively, to *M. Xu* (China; 2017) and *A. Peidou* (Canada; 2018). *H. Drewes* announced that the awards would be presented at the IAG Opening Session.

5. Proposal of the IAG Budget 2019 – 2022

H. Drewes summarized the IAG Financial Report 2015-2018, and presented the proposed IAG Budget 2019-2022 (see IAG Secretary General Report in this Handbook). He mentioned that there were no major changes, but in future most of the publication costs would go into open access of online publications rather than in printed publications.

6. Appointment of the Audit Committee

H. Drewes noted that the Audit Committee should audit and approve the IAG Financial Report 2015-2018 and the IAG Budget 2019-2022. He presented the names of the members of the Audit Committee as proposed by the IAG Executive Committee incl., *D. Blitzkow* (Chair), *J. Agren*, and *M. Amos*. The IAG Council Members approved the proposed members of the Audit Committee unanimously.

7. Appointment of the Resolutions Committee

H. Schuh noted that the Resolution Committee should prepare future IAG resolutions. He presented the names of the members of the Resolutions Committee as proposed by the IAG Executive Committee incl., *G. Blewitt*, *R. Gross*, *R. Pail*, *L. Sanchez*, and *A. Kealy*. The IAG Council Members approved the proposed members of the Resolutions Committee unanimously.

8. Review of the 2019 election process and results

C. Rizos gave the presentation of the results of the IAG Officers election process 2019. He reported about (i) procedures for nominations and elections, (ii) the Nominating Committee, (iii) the nomination process, (iv) the election results for IAG Officers (2019-2023), and (v) issues to be considered in future.

9. Review of IAG Statutes and Bylaws (Report of the Cassinis Committee)

H. Schuh invited *C. Rizos*, Chair of the Cassinis Committee, giving his report on the review of the IUGG Statutes and Bylaws. *C. Rizos* gave a presentation. He reported about (i) the tasks of the Cassinis Committee, (ii) the proposed changes to the IAG Statutes and Bylaws, and (iii) issues to be considered in future. *H. Schuh* asked the IAG Council Members to volunteer for being member on an ad-hoc committee to work on the final wording of the revised Statutes and Bylaws. The IAG Council Members appointed *J. Freymueller*, *P. Clarke*, and *M. Amos*. The final versions of the revised IAG Statutes and Bylaws are available at the IAG Office Homepage.

10. IAG Strategy Document

H. Schuh summarized the IAG strategy process, which started in 2015 and ended with a detailed document early in 2019. *He* highlighted the major challenges, visions and options of IAG in the next decade. The IAG Secretary General, *H. Drewes*, had sent the IAG Strategy Document to the Council members well before the meeting, and *H. Schuh* asked the Council to adopt it as the official IAG Strategy Document. It is available at the IAG Office Homepage.

11. Status of Journal of Geodesy and IAG Symposia Series

H. Drewes summarized the status and major changes of the Journal of Geodesy, and the IAG Symposia Series. He noted that in future there would be a continuous article publication (CAP) of the Journal of Geodesy. Until now, the articles were only published as complete volumes. He further noted that, starting with the proceeding of IUGG2019, the IAG Symposia Series would change from book publications to open access online publications. The symposia organizers will have to pay $50 per participant.

12. Status of IAG Reports (Travaux de l'AIG) and National Reports 2015-2019

H. Drewes gave a presentation about the status and content of the IAG Reports Vol. 41 (Travaux de l'AIG 2015-2019), which are available at the IAG Office Homepage. He noted that the report of BIPM is still missing, and that only few countries submitted National Reports. He invited the IAG Council Members to submit their National Reports still.

13. IAG Scientific Assembly 2021

H. Drewes repeated the notification that the Council members had elected Beijing, China, by electronic voting in August 2018 as the venue of the IAG Scientific Assembly 2021. The Chinese Society of Geodesy, Photogrammetry and Cartography will organize it together with the Chinese Academy of Surveying and Mapping from 28 June to 5 July 2021.

14. Any other business

J. Adam invited the IAG Council members to submit geodesy related news from their countries to the IAG Communication and Outreach Branch (COB) for publication in the IAG Newsletter and through the IAG social media channels.

Adjourn

H. Schuh thanked the participants for their contributions and closed the session at 10:00.

Minutes of the IAG Council Meeting at the IUGG General Assembly 2019 (session 2)

Place: Palais des Congrès, Montreal, Canada, Room 513C
Time: 16 July 2019, 18:00-20:00

Agenda

15. Report of the Audit Committee and discharge of the management
16. Approval of the IAG Budget 2019-2022
17. Approval of the revised Statutes and Bylaws
18. Report of the IAG Resolutions Committee
19. Approval of Resolutions
20. Report from IUGG Council and Executive Committee
21. IAG Representatives to external bodies
22. Preparation of the IAG and IUGG Closing Sessions
23. Any other business

Adjourn

Participants

IAG National Delegates: Austria (Johannes Böhm), Brazil (Roberto Luz), China (Yamin Dang), China-Taipei (Ming Yang), Czech Republic (Pavel Novak), Denmark (Niels Andersen), Finland (Jyri Näränen), France (Marie-Francoise Lalancette), Germany (Jürgen Müller), Greece (Dimitrios Tsoulis), Hungary (Jozsef Adam), Italy (Mattia Crespi), Rep. of Korea (Jungho Cho), New Zealand (Matt Amos), Poland (Pawel Wielgosz), Slovakia (Juraj Janak), Sweden (Jonas Agren), Switzerland (Elmar Brockmann), UK (Peter Clarke), USA (Jeffrey Freymueller)

IAG Executive Committee Members: Harald Schuh (IAG President), Zuheir Altamimi (IAG Vice President), Hermann Drewes (IAG Secretary General), Richard Gross (GGOS Chair), Axel Nothnagel (Representative of the IAG Services), Chris Rizos (IAG Immediate Past President)

Guests: Denizar Blitzkow, Franz Kuglitsch (IAG Assistant Secretary General; minute taker), Markku Poutanen (IAG Secretary General 2019-2023)

Minutes

15. Report of the Audit Committee and discharge of the management
D. Blitzkow reported about the work of the Audit Committee, and mentioned that the committee examined carefully the IAG Financial Report 2015-2018 including all the account documents without any objection. *He* applied for discharge of the Secretary General w.r.t. his financial management. The IAG Council Members approved the discharge of the management unanimously.

16. Approval of the IAG Budget 2019-2022
D. Blitzkow reported that the Audit Committee examined also the IAG Budget 2019-2022, which *H. Drewes* had proposed in the session on July10 (see agenda item 5) and moved for the approval. The IAG Council Members approved the IAG Budget 2019-2022 unanimously.

17. Approval of the revised Statutes and Bylaws
C. Rizos invited the IAG Council Members to submit concerns about the Statutes and Bylaws at any time as they can be implemented in future. Based on the final comments made by *C. Rizos* and *J. Freymueller*, the IAG Council Members approved the revised Statutes and Bylaws unanimously.

18. Report of the IAG Resolutions Committee
H. Schuh invited the Chair of the IAG Resolution Committee giving his report on the IAG Resolution Committee. *R. Gross* discussed the five proposed resolutions incl.,

- Resolution 1: The International Terrestrial Reference Frame (ITRF),
- Resolution 2: Third Realization of the International Celestial Reference Frame,
- Resolution 3: Establishment of the International Height Reference Frame (IHRF),
- Resolution 4: Establishment of the Infrastructure for the International Gravity Reference Frame, and
- Resolution 5: Improvement of the Earth's Rotation Theories and Models,

H. Schuh noted that the Resolution 1 on the ITRF was also submitted to IUGG.

19. Approval of Resolutions

The IAG Council Members approved unanimously the IAG Resolutions discussed under agenda item 18. Resolutions are available at the IAG Office Homepage.

20. Report from IUGG Council and Executive Committee

H. Schuh summarized the major outcome of the IUGG Council and Executive Committee Meetings and first numbers on the 2019 IUGG General Assembly. The size of this IUGG General Assembly was quite average but slightly smaller than it was in Prague 2015. The participation of early-career scientists was very good. *He* presented the names of the newly elected members of the IUGG Bureau and Finance Committee (2019-2023), incl. *C. Rizos* as President-Elect, *N. Andersen* as Treasurer, and *J. Adam* as Finance Committee Member from IAG. He mentioned that the IUGG General Assembly 2023 will be organized in Berlin, Germany.

21. IAG Representatives to external bodies

H. Drewes reported that the IAG Executive Committee revised the IAG Representatives to the IAG Services, IUGG Commissions and Committees, UN-GGIM and UN-OOSA, other external bodies (ABLOS, IAU, ISO, SIRGAS), and IUGG Liaisons (CCTF, COSPAR, GEO, PAIGH, ISC-WDS). The new Executive Committee 2019-2023 may make further changes and publish it at the IAG Website.

22. Preparation of the IAG and IUGG Closing Sessions

H. Drewes announced the Closing Sessions of IAG and IUGG, which will be held on 17 July 2019, 3:00 pm and 4:30 pm, respectively, and invited all assembly participants to attend. At the IAG Closing Session, all conveners of IAG related symposia will summarize the highlights.

23. Any other business

J. Freymueller noted that there would be IAG proceedings of this IUGG General Assembly as an electronic open access publication by Springer. *H. Drewes* announced that the next Geodesist's Handbook including the reports of the General Assembly 2019 and the new IAG structure 2019-2023 would be published as an electronic open access publication within the Journal of Geodesy in 2020. *H. Schuh* noted that the local organizers of this IUGG General Assembly would soon send out a questionnaire to all participants to improve the quality of IUGG General Assemblies in future. *He* invited everyone to participate in this questionnaire.

Adjourn

H. Schuh thanked the participants for their contributions and closed the session at 18:30.

Summary of the IAG Executive Committee Sessions

Hermann Drewes (Secretary General) · **Franz Kuglitsch** (Assistant Secretary)

Place: Palais des Congrès in Montréal, Québec, Canada, Floor 5, Room 522B

Time: 2019, July 9, 08:30-18:00 (Topics 1-17), July 12, 18:00-20:00 (Topics 18-28) and July 15, 18:00-20:00 (Topics 29-40)

Attendees (voting): H. Schuh (IAG President), Z. Altamimi (IAG Vice President), H. Drewes (IAG Secretary General), C. Rizos (Immediate IAG Past President), G. Blewitt (President Commission 1), R. Pail (President Commission 2), C. Huang (Vice President Commission 3, temporarily), M. Santos (President Commission 4, temporarily), P. Novák (President ICC on Theory), R. Gross (Chair of GGOS), J. Adám (President of the COB), R. Barzaghi and A. Nothnagel (Representatives of the Services), Y. Dang (Member-at-Large, temporarily).

Attendees (non-voting): F. Kuglitsch (IAG Assistant Secretary General, minute taker, temporarily), M. Sideris (IAG Past President).

Guests (temporarily)**:** M. Poutanen (IAG Secretary General 2019-2023), J. Müller (Chair of the Planning Group for a new IAG Subcomponent on Novel Sensors and Technologies), C. K. Shum (Chair of the Planning Group for the Re-establishment of the International Altimetry Service), G. Dick (Deputy of the Assistant Secretary General, minute taker), J. Kusche (Editor-in-Chief of the Journal of Geodesy), J. Freymueller (Editor-in-Chief of the IAG Symposia Series), A. Eicker (Chair of the Planning Group for the Inter-Commission Committee on Geodesy for Climate Research).

Regrets: M. Hashimoto (President Commission 3), R. Neilan (Representative of the Services), M.C. Pacino (Member-at-Large).

Summary of Agenda Items:

1. Welcome and adoption of agenda

The 8th IAG EC Meeting in the term 2015-2019 took place on the occasion of the IUGG General Assembly 2019 at the Palais des Congrès, room 522B, in Montréal, Canada, on July 9, 12 and 15, 2019. The agenda was distributed previously by e-mail and was unanimously adopted. *H. Schuh*, the President of the IAG, welcomed the members of the IAG Executive Committee in the first session (11 out of 16 voting members, 2 non-voting members and 4 guests). The EC Members approved the minutes of the 7th IAG EC Meeting in the term 2015-2019, which took place on 10 December 2018 in Washington DC, USA.

2. IUGG2019 organizational issues

H. Drewes summarized the organizational issues of IUGG. He reported about (i) IAG's involvement in the science program (incl. IAG Symposia, Joint-Symposia, poster sessions) compared to previous IUGG General Assemblies and compared to other Associations, (ii) IAG Business Meetings, and (iii) IUGG and IAG Travel Grants (IAG paid nearly CAD 40,000).

3. Agenda of the Council meetings, July 10, 08:30–10:00 & July 16, 18:00–20:00

H. Drewes presented and discussed the agenda of the Council Meeting. *H. Schuh* noted that IAG Strategy Document is now finished and should be approved by the Council.

4. Agenda of Opening and Closing Sessions, July 11, 18:00–20:00 & July 17, 15:00–16:30

H. Drewes presented and discussed the draft agenda of the Opening and Closing Sessions.

5. Proposal for members of the Audit Committee TBD by the Council

H. Drewes presented and discussed the list of proposed members of the Audit Committee, which has to be appointed by the IAG Council. *H. Schuh* noted that the members of the Audit Committee should be IAG Council Delegates or National Correspondents, and should preferably represent all continents. *M. Sideris* suggested asking some more people before the Council Meeting starts.

6. Nomination of members of the Resolution Committee for IAG and IUGG

H. Drewes presented and discussed the proposed members of the Resolutions Committee, which has to be appointed by the IAG Council. They should represent all IAG Commissions, GGOS, continents and gender. *H. Schuh* noted that IAG has received so far two proposals for resolutions, which should be approved by IAG: (i) on the 3rd realizations of the International Celestial Reference Frame (ICRF), which was already approved by the International Astronomical Union (IAU) in 2018, and (ii) on the improvement of the Earth Rotation Theories and Models. In addition, a resolution on the International Terrestrial Reference Frame (ITRF) was proposed, which should be approved by IAG and IUGG.

7. Levallois Medal, Guy Bomford Prize, Young Authors Award, new IAG Fellows

H. Drewes presented the list of proposed IAG awardees and fellows. *He* noted that *C. Reigber* (Germany) will be awarded the Levallois Medal 2019, the Guy Bomford Prize will be given to *M. Sprlak* (Australia), and the Young Authors Awards will be given to *M. Xu* (China; 2017) and *A. Peidou* (Canada; 2018). *H. Schuh* encouraged the EC Members to nominate more scientists for IAG Awards in future. *H. Drewes* said that the deadline for nominating additional IAG Fellows is before the last EC meeting on Monday, July 15, when the EC shall appoint the Fellows officially. They will be presented at the Closing Session on Wednesday, July 17. *M. Sideris* proposed giving the Young Authors Awardees in future a lecture at the General Assembly and introducing clear criteria on how to become an IAG Fellow.

8. Results of the 2019 IAG Officers election process

C. Rizos gave the presentation of the results of the 2019 IAG Officers election process. He reported about (i) procedures for nominations and elections, (ii) the Nominating Committee, (iii) the nomination process, (iv) the election results for IAG Officers (2019-2023), and (v) issues to be considered in future. *H. Schuh* noted that IAG should definitely go for electronic voting in future, and that the two-step procedure in the election process when there are more than two nominations should be supported to get absolute majorities. He suggested starting the election process earlier in future.

9. Report on the review of the IAG Statutes and Bylaws (Cassinis Committee)

C. Rizos reported about (i) the tasks of the so-called Cassinis Committee, (ii) the proposed (minor) changes to the IAG Statutes and Bylaws, and (iii) issues to be considered in future. The EC Members made a few further minor changes to the IAG Statutes and Bylaws. *H. Schuh* suggested that nominations of candidates for the position of the GGOS President should be made by the GGOS Coordinating Board in consultation with the EC Members. The EC Members agreed on adding this change to the Bylaws. The final version of the revised IAG Statutes and Bylaws will be approved by the IAG Council. *C. Rizos* suggested considering to include the expectations of the National Correspondents and Adhering Bodies in the Bylaws.

10. Status of IAG Report 2015-2019 (Travaux de l'AIG 2015-2019)

H. Drewes gave a presentation about the status and content of the IAG Report Vol. 41 (Travaux 2015-2019). The final version will be available at the IAG Office Homepage. He further noted that very few countries submitted National Reports. The EC Members agreed on introducing a DOI for the Travaux (possibly via the library of the GFZ German Research Centre for Geosciences). *H. Drewes* confirmed that all Springer publications have a DOI.

11. Reports and recommendations of the Commissions

J. Müller gave a presentation about the status of the Planning Group for a new **IAG Project** on Novel Concepts and Quantum Technology in Geodesy and the proposed Terms of Reference. He reported about (i) new approaches to observe the Earth gravity fields, and (ii) the preliminary structure of the new entity incl. possible working groups. The EC Members approved the progress made by the Planning Group and asked *J. Müller* (i) to develop a formal structure of this new entity, and (ii) prepare final terms of reference to be approved at the next IAG EC Meeting in December 2019 in San Francisco CA, USA. *G. Blewitt* and *H. Schuh* suggested considering optical clocks in this project, and emphasizing the novel sensors besides the quantum technology in the title. *J. Müller* agreed on including these issues. The EC Members agreed on re-naming the IAG Project to *Novel Sensors and Quantum Technology for Geodesy*.

G. Blewitt gave the presentation about **Commission 1** (Reference Frames). *He* summarized (i) the activities of Commission 1 between 2015 and 2019, (ii) the structural components of Commission 1, and (iii) suggestions for the future.

R. Pail gave the presentation on **Commission 2** (Gravity Field). *He* reported about (i) recent activities of Commission 2, and (ii) the proposal to establish an Inter-Commission Committee on "Geodesy for Climate Research" (ICCC) incl. objectives, planned activities.

On behalf of *M. Hashimoto, R. Gross* gave the presentation about **Commission 3** (Earth Rotation and Geodynamics). *He* reported about (i) the activities of the five Sub-commissions, Joint Study Groups, Joint Working Groups, (ii) the proposal to establish an Inter-Commission Committee on Marine Geodesy (ICCM). *H. Schuh* noted that Sub-commissions 3.2 and 3.5 should be strengthened in future, as the volcanology and seismology communities are very active in this field. *H. Drewes* said that according to the discussion with IASPEI, Subcommission 3.5 would become an Inter-Association Sub-Commission (in IAG) or Commission (in IASPEI) on Seismo Geodesy. A meeting is planned with IASPEI on July 13, 18:00 (after the Joint Symposium JS04 Seismo-Geodesy) or on July 14, 18:00. The EC Members approved the establishment of an Inter-Commission Committee on Marine Geodesy (ICCM), and asking Yuanxi Yang to develop a formal structure and draft terms of reference.

On 12 July, *A. Eicker* reported about her ideas to establish an **Inter-Commission Committee on Geodesy for Climate Research (ICCC)**. She reported about (i) the importance of geodesy for climate research, and (ii) possible objectives and planned activities of ICCC. *Z. Altamimi* asked *A. Eicker* to contact the Commissions to get more people involved in ICCC. In addition, he suggested focusing on a few major topics. *H. Schuh* noted having 4-5 working groups is a good start. *R. Gross* suggested including the GGOS Chair of the Science Panel in the ICCC activities. The EC Members established the Inter-Commission Committee on Geodesy for Climate Research (ICCC) and appointed *A. Eicker* as ICCC President for the period 2019-2023. The EC Members asked *A. Eicker* to finalize a formal structure and to draft terms of reference of ICCC until the IAG EC Meeting to be held in December 2019 in San Francisco CA, USA.
H. Schuh summarized the presentation about **Commission 4** (Positioning & Applications; as prepared by *M. Santos*). *He* reported about (i) the activities of Commission 4 between 2015 and 2019, (ii) recommendations for the next term, and (iii) the 2nd Commission 4 Symposium to be organized in September 2020 in Potsdam, Germany.

12. Report and recommendations of the ICCT
P. Novák gave a presentation about the ICCT. *He* reported about (i) the activities of the ICCT study groups between 2015 and 2019, (ii) the ICCT website, (iii) the Hotine-Marussi 2018 Symposium and its proceedings, and (iv) recommendations for the next term. The EC Members agreed on asking *J. Kusche*, Editor in Chief of the Journal of Geodesy (JoG), to include a member of ICCT to the JoG Editorial Board.

13. Appointment of the ICCT President for the period 2019-2023
The EC Members re-appointed *P. Novák* as ICCT President for the period 2019-2023.

14. Report and recommendations of the Services' representatives
C. K. Shum reported about the rationale, objectives, terms of reference, and future steps to reestablish the International Altimetry Service (IAS). He confirmed that IAS should provide a combined product of various analysis centers. *H. Drewes* urged to define clearly the products. *H. Schuh* suggested including people who already have experience in running IAG Services. The EC Members asked *C.K. Shum* to develop a formal structure and to draft terms of reference of the new IAS until the IAG EC Meeting in San Francisco CA, USA, December 2019.

R. Barzaghi gave the first presentation about the Services. He (i) reported about the activities of the International Gravity Field Service (IGFS) between 2015 and 2019 including the International Gravimetric Bureau (BGI), International Service for the Geoid (ISG), International Geodynamics and Earth Tide Service (IGETS), International Center for Global Earth Models (ICGEM), International DEM Service (IDEMS), and International Combination Service for Time-variable Gravity Field Solutions (COST-G), and (ii) gave recommendations for future topics. *Z. Altamimi* offered asking *T. Otsubo* to report on topics related to gravity in future. The EC Members agreed. *H. Schuh* noted that COST-G is a product center of IGFS. *R. Barzaghi* agreed on sending an updated slide.

A. Nothnagel gave the second presentation about the Services. *He* (i) reported about recent activities of the International Earth Rotation and Reference Systems Service (IERS), International GNSS Service (IGS), International Laser Ranging Service (ILRS), InternationalVLBI Service for Geodesy and Astrometry (IVS), and Permanent Service for Mean Sea Level (PSMSL). *He* further presented the revised terms of reference for the International VLBI Service for Geodesy and Astrometry (IVS). IVS would like to introduce a new "Office for Outreach and Communications". *H. Schuh* noted that this outreach team should be well linked to the communication and outreach entities of IAG, GGOS etc. *H. Schuh* also noted that having 17 people in the IVS Directing Board is a lot and might become inefficient. The EC Members approved the revised IVS terms of reference unanimously.

15. Report and recommendations of GGOS
R. Gross gave a presentation about the current activities of the Global Geodetic Observing System (GGOS). *He* reported about (i) the GGOS Structure, (ii) the new GGOS Affiliate "GGOS Japan", (iii) the GGOS 2018 Days in Tsukuba, Japan, (iv) the Committee on Essential Geodetic Variables (EGVs), (v) the Working Group on DOIs for Geodetic Data Sets, (vi) GGOS External Relations, and (vii) the 2019 meetings calendar. *He* noted that within the last 1.5 years, the visibility of geodesy within the Group on Earth Observations (GEO) has increased a lot. *H. Schuh* clarified that GGOS has the mandate to represent IAG at the GEO Programme Board. In addition, *M. Sideris* represents IUGG within GEO. *H. Schuh* noted that it would be good for GGOS to have its own products.

16. Appointment of the GGOS Chair for the period 2019-2023
R. Gross gave a presentation about the process of finding a new GGOS Chair for 2019-2023. Only one candidate was nominated so far. *Z. Altamimi* and *H. Schuh* suggested postponing the election to find at least two additional candidates. *H. Schuh* noted that GGOS is IAG's flagship component and that the GGOS Chair has to do two business trips per year. The EC Members agreed on (i) postponing the election of the GGOS Chair 2019-2023 to find at least two additional candidates, (ii) offering IAG travel support to EC Members from developing countries (if needed), and (iii) clarifying with the Audit Committee if IAG travel support could be also provided to the GGOS Chair (who has exceptional responsibilities).

17. Report of the COB
J. Adám reported about current COB activities. *He* highlighted (i) the activities of the COB between 2015 and 2019, (ii) the IAG website, (iii) the IAG newsletter, (iv) GIM International, (iv) social media activities, and (v) the UN GGIM WG (focus group on Outreach and Communication). *R. Pail* suggested hosting the Commission websites centrally as part of the IAG website. Then, the Commission websites would not have to move with the Commission Presidents from one institution to the next. In addition, nowadays many institutes have legal restrictions to host such websites, as they are responsible for the content. *J. Adám* agreed on asking *S. Rozsa* whether it would be possible to host the Commission websites as part of the IAG website.

18. Report of the Members-at-Large
There were no reports available from the Members-at-Large.

19. Report of the Journal of Geodesy Editor-in-chief
H. Drewes summarized the presentation of the Journal of Geodesy Editor-in-Chief, *Jürgen Kusche*. The report includes (i) proposed changes of the Editorial Board 2020-2023, (ii) numbers of submitted and accepted manuscripts and the reviews, the impact factor and top ranking of highest citing of the Journal of Geodesy, (iii) Special Issues planned, (iv) editorial practices and new policies. The EC members congratulated the Editorial Board on the high impact factor of the Journal of Geodesy.

20. Proposal of the new Board of Editors of JoG by the old Board
J. Kusche presented the proposed changes of the Editorial Board 2020-2023. There is no limit in the number of editors. *He* noted that next week there will be a meeting of the Editorial Board to discuss next steps. In addition, the Editorial Board will elect the Editor-in-Chief. The EC Members discussed the suggested new members of the Editorial Board and kept the composition as proposed.

21. Report of the Editor of the IAG Symposia Series
J. Freymueller gave the presentation about the IAG Symposia Series. *He* reported about (i) the symposia volumes that have been published since 2013, (ii) the review process, and (iii) the future outlook incl. open access and the IUGG2019 Montreal Volume.

22. Proposal of the 2019-2023 Editor and Assistant Editor of the IAG Symposia Series
On 15 July 2019, *J. Freymueller* mentioned that *he* would we willing to continue as the Editor-in-Chief of the IAG Symposia Series for 2019-2023. Also, *L. Sanchez* would be willing to continue as Assistant Editor.

23. Report on the UN-GGIM (Subcommittee on Geodesy, GGRF, GGIM-GS)
H. Schuh noted that UN-GGIM is in the process of establishing a Global Geodetic Center of Excellence based on a 2015 resolution. IAG is actively contributing through *Z. Altamimi*, *R. Gross* and *H. Schuh*. The future goal should

be to have a UN convention on geodesy. He mentioned that the colleagues from the United Nations are often not aware of what kind of geodetic products and services already exist.

24. Report on IUGG activities

F. Kuglitsch reported, that since the last EC Meeting in December 2018, most of his activities were related to (co)organizing this IUGG General Assembly 2019. *He* mentioned that there are four candidate cities to host the IUGG General Assembly 2023: Athens, Berlin, Geneva, and Guadalajara. The candidates presented their bids today, and the IUGG Site Comparison Committee will announce tomorrow a shortlist of the top two candidates the IUGG Council can vote on. *He* invited the EC Members to attend this IUGG Award Ceremony. *H. Schuh* noted that the Chair of the IUGG Finance Committee mentioned in his presentation to the IUGG Council that there is no audit of the money that goes from IUGG to its Associations, which corresponds to around 50% of the total IUGG budget. *F. Kuglitsch* mentioned that getting a professional audit of the IUGG Budget by e.g., PWC, EY, would cost IUGG around 20% of its total budget. For this reason, IUGG will most likely not hire a professional auditor in future. *H. Schuh* suggested IUGG nominating a member in the audit committees of the Associations.

25. Reports on liaised bodies (ABLOS, IAU Comm. 19, GEO, ISO, UN)

H. Drewes summarized the reports received from liaised bodies including ABLOS, GEO, IAU Commission 19, ISO, and UN-GGIM-Geospatial Societies.

26. Appointment of IAG Representatives to IAG Services, IUGG Commissions & others

H. Drewes discussed the list of IAG Representatives to Scientific Bodies. The EC Members agreed on the list of representatives; however, the new EC may revise the list. In particular, another representative to the International DORIS Service (IDS) has to be appointed. *F. Kuglitsch* noted that IUGG Commission Chairs were informed about the nominated IAG representatives and will invite them to their business meetings during the IUGG General Assembly. There, the future membership of a Commission will be decided. *He* further noted that the future of the IUGG Committees and its members will be discussed by the newly elected IUGG Bureau. If new Committee members are needed, the Associations will be informed.

27. Status of the IAG Scientific Assembly 2021

Y. Dang gave a presentation about the status of organizing the IAG Scientific Assembly 2021 to be held in Beijing, China, from June 28 to July 3, 2021. *H. Drewes* noted that the IAG Secretary General (2019-2023) will be the Secretary of the IAG Assembly. In 2020, he should visit the venue and make organizational arrangements. All symposia should be led by IAG. There will not be any joint symposia with other Associations. *He* mentioned that there should be only two (or three at the very maximum) parallel sessions. In total, having three big (for up to 700 people) and five smaller rooms for business meetings should be sufficient.

28. Any other business

H. Schuh noted that there are still candidates available for nomination of GGOS Chair, given that IAG can provide travel support.

29. Actual status report

H. Schuh summarized the major outcomes of the IUGG Executive Committee and Council Meetings and presented first numbers of the General Assembly 2019. In addition, *he* mentioned the three resolutions adopted by IUGG. *He* informed that the next IUGG General Assembly will be held 2023 in Berlin, Germany, and that the Associations should report to IUGG about possible improvements. *F. Kuglitsch* noted that there is an ongoing discussion about further reducing the number of days of the General Assembly.

30. Approval of the new Board of Editors of the JoG

J. Kusche presented the new Board of Editors of the JoG. *He* noted that the old Board of Editors approved the newly suggested members. *He* will continue as Editor-in-Chief. The EC Members approved the new Board of Editors of the JoG unanimously. *H. Drewes* noted that the new contracts between Springer and the IAG w.r.t. the Journal of Geodesy and the IAG Symposia Series should be signed by the new IAG President and Secretary General.

31. Approval of the Editor-in-Chief and Assistant Editor-in-Chief of the IAG Symposia Series

The EC Members approved *J. Freymueller* and *L. Sanchez* as the Editor-in-Chief and Assistant Editor-in-Chief for 2019-2023 unanimously.

32. Summary of the Report of the Audit Committee

H. Drewes noted the report of the Audit Committee will be presented to the Council tomorrow.

33. Report of the IAG Resolution Committee

R. Gross gave a presentation about the five IAG Resolutions, and further discussed them with the EC Members. He noted that the Resolution 1 on the ITRF was identically submitted to IUGG. The EC Members agreed on changing the title of resolution 4 to "Establishment of the

Infrastructure for the International Gravity Reference Frame".

34. Discussion of proposed resolutions for approval by the IAG Council
The EC Members proposed the IAG Council to adopt the five resolutions.

35. Status of reviewed Statutes and Bylaws
J. Freymueller noted that the two steps election procedure part was rephrased for clarity. The EC Members agreed that in case of an election tie, only the President should break the tie. *J. Freymueller* agreed on sending the latest version to the EC Members.

36. Sponsorship of symposia and workshops
H. Drewes summarized the upcoming IAG Events. *He* noted that if a meeting gets sponsored by IAG, early-career scientists can apply for IAG Travel Awards.

37. Preparation of the IAG Closing Session
H. Drewes summarized the agenda of the IAG Closing Session (see agenda item 4) and asked all symposia conveners to prepare a brief report on the highlights.

38. Any other business
H. Schuh noted that there is interest of IAGA and IASPEI for organizing a joint Scientific Assembly together with IAG in 2025 in Lisbon, Portugal, which should be considered in future.

39. Appointment of Honorary Officers (President, Secretary General, Fellows, Bylaws 22)
The EC Members discussed and approved the final list of new IAG Fellows (available at IAG web site). The EC Members appointed *H. Schuh* as IAG Honorary President and *H. Drewes* as IAG Honorary Secretary General.

40. Closing the EC of the legislative period 2015-2019
H. Schuh presented his ideas for the future and concluding remarks as IAG President, and he thanked especially *J. Adám* for being President of the COB for 16 years, and *H. Drewes* for being IAG Secretary General for 12 years. He thanked the EC Members for their contributions over the last term and closed the session at 20:00. The EC Members thanked *H. Schuh* for his dedication over the last years.

IUGG Resolutions at the XXVII General Assembly 2019

Resolution 1: Reducing the Carbon Foot Print by the Research Community

The International Union of Geodesy and Geophysics

Considering
The clearly established impact of human activity on climate change and biosphere degradation,
Acknowledging
The irreversible consequences of continuing the current trajectory of greenhouse gas emission for the ecosystems of the planet and human societies,
Noting
That the Intergovernmental Panel on Climate Change (IPCC), in its recent special report on the impact of global warming of 1.5°C (IPCC, 2018; https://www.ipcc.ch/sr15/),

- Demonstrated the dramatic differences between the consequences of warming of 1.5°C and 2.0°C above pre-industrial levels, and
- Showed that limiting the warming to 1.5°C could be obtained only by strongly reducing carbon dioxide emissions before 2030,

Urges

- IUGG and affiliated Scientific Associations to take carbon foot print criteria into account when choosing the venue of future meetings, and
- The participants of the 27th IUGG General Assembly, research institutions and individual researchers to contribute to an unprecedented effort to evaluate and reduce greenhouse gas emission impact on the environment.

Resolves
The research community, which is well aware of the origins and impact of climate change, should exhibit an exemplary attitude by modifying its professional practices in order to rapidly reduce its carbon footprint.

Resolution 2: The International Terrestrial Reference Frame (ITRF)

The International Union of Geodesy and Geophysics

Considering

- The significant efforts of the International Association of Geodesy (IAG) in developing and maintaining fundamental geodetic products, in particular the International Terrestrial Reference Frame (ITRF), for scientific and societal benefits, and
- The importance of inter-operability of various geospatial data-sets and geo-referencing applications,

Acknowledging
The adoption by the IUGG of Resolution 2 in Perugia 2007 of the International Terrestrial Reference System (ITRS) as the preferred Geocentric Terrestrial Reference System (GTRS) for scientific and technical applications,
Noting

- That the ITRF is the numerical realization of the ITRS, developed, maintained and made available to users by the International Earth Rotation and Reference Systems Service (IERS), an IAG service, and
- That the ITRF is widely used as the standard in various geo-referencing applications,

Resolves
To recommend to the user community that the ITRF be the standard terrestrial reference frame for positioning, satellite navigation and Earth Science applications, as well as for the definition and alignment of national and regional reference frames.

Resolution 3: Thanks

The International Union of Geodesy and Geophysics

Resolves
To record gratefully its appreciation for the organization, arrangements, and hospitality at its 27th General Assembly. On behalf of all participants the Council expresses its warm thanks to the Local Organizing Committee, the Scientific Program Committee, the Canadian Geophysical Union (CGU), the Canadian Meteorological and Oceanographic Society (CMOS) and all others for making the 27th General Assembly a success in the beautiful city of Montreal.

IAG Resolutions at the XXVII IUGG General Assembly 2019

Resolution 1: The International Terrestrial Reference Frame (ITRF)

The International Association of Geodesy,

Considering,

- The significant efforts of the International Association of Geodesy (IAG) in developing and maintaining fundamental geodetic products for scientific and societal benefits, in particular the International Terrestrial Reference Frame (ITRF);
- The importance of interoperability of various geospatial data-sets and geo-referencing applications;

Acknowledging,

The adoption by the IUGG Resolution 2 in Perugia 2007 of the International Terrestrial Reference System (ITRS), as the preferred Geocentric Terrestrial Reference System (GTRS) for scientific and technical applications;

Noting,

- That the ITRF is the numerical realization of the ITRS, developed, maintained and made available to the users by the International Earth Rotation and Reference Systems Service (IERS), an IAG service;
- That the ITRF is widely used as the standard in various geo-referencing applications;

Resolves,

To recommend to the user community that the ITRF be the standard terrestrial reference frame for positioning, satellite navigation and Earth science applications, as well as for the definition and alignment of national and regional reference frames.

Resolution 2: Third Realization of the International Celestial Reference Frame

The International Association of Geodesy,

Considering,

- That the International Union of Geodesy and Geophysics adopted at the 25th General Assembly in Melbourne 2011 Resolution 2 on the second realization of the International Celestial Reference Frame;
- That the International Astronomical Union (IAU) adopted Resolution B2 at its XXXth General Assembly (2018) (https://www.iau.org/static/resolutions/IAU2018_Resol B2 _English.pdf) that resolves to consider the "Third Realization of the International Celestial Reference Frame (ICRF3)" as the fundamental realization of the International Celestial Reference System (ICRS) (see note 1);
- That the celestial reference system and the nutation-precession model have a large influence on geodetic and geodynamic observations, analyses and interpretations;
- That the ICRF3 was constructed by the International Astronomical Union (IAU) involving working group members of the International Earth Rotation and Reference Systems Service (IERS) and the International VLBI Service for Geodesy and Astrometry (IVS) communities;

Recommends,

- That the ICRF3 should be used as a standard for all future applications in geodesy and astrometry;
- That the organizations responsible for geodetic VLBI observing programs take appropriate measures to continue existing and develop improved VLBI observing and analysis programs to both maintain and improve ICRF3;

- That highest consistency between the ICRF, the International Terrestrial Reference Frame (ITRF), and the Earth Orientation Parameters (EOP) should be a primary goal in all future realizations.

Note 1: The Third Realization of the International Celestial Reference Frame by Very Long Baseline Interferometry, Presented on behalf of the IAU Working Group, Patrick Charlot, Chris Jacobs, David Gordon et al. Astronomy & Astrophysics (in preparation).

Resolution 3: Establishment of the International Height Reference Frame (IHRF)

The International Association of Geodesy,

Considering,
- The IAG Resolution for the Definition and Realization of an International Height Reference System (IHRS) released at the 26th IUGG General Assembly in July 2015;

Acknowledging,
The achievements of
- GGOS Focus Area "Unified Height System" and its JWG 0.1.2 "Strategy for the Realization of the International Height Reference System (IHRS)",
- IAG JWG 2.2.2 "The 1 cm geoid experiment",
- IAG SC 2.2 "Methodology for geoid and physical height systems",
- ICCT JSG 0.15 "Regional geoid/quasi-geoid modelling – Theoretical framework for the sub-centimetre accuracy";

in realizing this resolution;

Noting,
The need of an operational infrastructure to ensure the determination, maintenance and availability of an International Height Reference Frame (IHRF) in the long-term basis;

Urges,
All countries to engage with the IAG and concerned components, in particular the International Gravity Field Service (IGFS), in order to promote and support the implementation of the IHRF by
- Installing IHRF reference stations at national level,
- Conducting the necessary gravimetric surveys to guarantee the precise determination of potential values,
- Making data available open access,
- Contributing to the development of analysis strategies to improve the estimation of reference coordinates and modelling of the Earth's gravity field,
- Describing, archiving and providing geodetic products associated to the IHRF.

Resolution 4: Establishment of the Infrastructure for the International Gravity Reference Frame

The International Association of Geodesy,

Considering,
The IAG Resolution No. 2 for the establishment of a global absolute gravity reference system released at the 26th IUGG General Assembly in July 2015;

Acknowledging,
The achievements of
- JWG 2.1.1 "Establishment of a global absolute gravity reference system",
- Sub-Commission 2.1 "Gravimetry and Gravity Networks",
- International Gravity Field Service (IGFS)

in realizing this resolution;

Noting,
That the realization of the International Gravity Reference System (IGRS), the International Gravity Reference Frame (IGRF), is based on measurements with absolute gravimeters (AG) monitored at reference stations and during international comparisons, which needs the support of national and international institutions;

Urges,
International and national institutions, agencies and governmental bodies in charge of geodetic infrastructure to
- Establish a set of absolute gravity reference stations on the national level,
- Perform regular absolute gravity observations at these stations,
- Participate in comparisons of absolute gravimeters to ensure their compatibility,
- Make the results available open access.

Resolution 5: Improvement of the Earth's Rotation Theories and Models

The International Association of Geodesy,

Recognizing,

- That the continuous improvement of the terrestrial and celestial reference systems and frames pursuing the accuracy and stability goals set by GGOS is necessary for determining and investigating the global change of the Earth;
- That the consistent definition and determination of the rotation between the two reference frames is tightly linked to geodynamics and necessary for the accurate realization of terrestrial frames and the determination of global geodetic variables;
- That the current Earth rotation theories are unable to model and predict the Earth orientation parameters (EOP) with an accuracy close to the GGOS requirements, in spite of the improved accuracy and precision of the individual and combined solutions derived from single or multiple techniques;
- That the precession nutation theories IAU2000 and IAU2006 suffer from internal inconsistencies and systematics whose correction is available, but also from inconsistencies due to incorporating outdated models instead of the state-of-art models used in EOP determination;
- That the theoretical models of the different EOPs and their observations are not always referred to the current IAG standards, in particular regarding terrestrial reference frames;

Noting,

- The results of the IAG Commission 3 Joint Working Group on Theory of Earth and validation, joint with the International Astronomical Union (IAU) Commission A2, summarized in its 2015-2019 report (see note 1);
- The need of taking advantage of the advances accomplished or yet in progress on different aspects of the theoretical and empirical modelling and prediction of the Earth's rotation to get closer to the GGOS goals;

Resolves,

- To encourage a prompt improvement of the Earth rotation theory regarding its accuracy, consistency, and ability to model and predict the essential EOP,
- That the definition of all the EOP, and related theories, equations, and ancillary models governing their time evolution, must be consistent with the reference frames and the resolutions, conventional models, products, and standards adopted by the IAG and its components,
- That the new models should be closer to the dynamically time-varying, actual Earth, and adaptable as much as possible to future updating of the reference frames and standards.

Note 1: Report of Commission 3 Joint Working Group 3.1 Theory of Earth rotation and validation (Joint with the IAU). In: IAG Reports Vol. 41 (Travaux de l'AIG 2015-2019, IAG Web page)

Structures for the Period 2019 – 2023

International Union of Geodesy and Geophysics (IUGG)

Executive Committee

Bureau

President:	*Kathryn Whaler*	UK
President-Elect:	*Chris Rizos*	Australia
Secretary General:	*Alexander Rudloff*	Germany
Treasurer:	*Niels Andersen*	Denmark
Members:	*Stephen McNutt*	USA
	Eduard Petrovsky	Czech Republic
	Jun Xia	China

Immediate Past President: *Michael Sideris* Canada

Presidents of the International Associations

IACS:	*Regine Hock*	USA
IAG:	*Zuheir Altamimi*	France
IAGA:	*Mioara Mandea*	France
IAHS:	*Günter Blöschl*	Austria
IAMAS:	*Joyce Penner*	USA
IAPSO:	*Trevor McDougall*	Australia
IASPEI:	*Kenji Satake*	Japan
IAVCEI:	*Patrick Allard*	France

Finance Committee

Chair:	*Corina Risso*	Argentina
Members:	*József Ádám*	Hungary
	Priscilla Grew	USA

Secretariat of IUGG

The Secretariat of IUGG is located in Germany:
Helmholtz Centre Potsdam
GFZ German Research Centre for Geosciences
Telegrafenberg, A17
14473 Potsdam, Germany

Executive Secretary:	*Franz G. Kuglitsch*	Germany
Assistant:	*Katrin Gundrum*	Germany

The Executive Secretary of IUGG is a non-voting Member of the Bureau of the Union.

International Associations

International Association of Cryospheric Sciences

President:	*Regine Hock*	USA
President-Elect:	*Liss M. Andreassen*	Norway
Secretary General:	*Richard Essery*	New Zealand

International Association of Geodesy

President:	*Zuheir Altamimi*	France
Secretary General:	*Markku Poutanen*	Finland

International Association of Geomagnetism and Aeronomy

President:	*Mioara Mandea*	France
Secretary General:	*Monika Korte*	Germany

International Association of Hydrological Sciences

President:	*Günter Blöschl*	Austria
President Elect:	*Berit Arheimer*	Sweden
Secretary General:	*Christophe Cudennec*	France

International Association of Meteorology and Atmospheric Sciences

President:	*Joyce Penner*	USA
Secretary General:	*Steven Ackerman*	USA

International Association for the Physical Sciences of the Oceans

President:	*Trevor McDougall*	Australia
Secretary General:	*Stefania Sparnocchia*	Italy

International Association of Seismology and Physics of the Earth's Interior

President:	*Kenji Satake*	Japan
Secretary General:	*Johannes Schweitzer*	Norway

International Association of Volcanology and Chemistry of the Earth's Interior

President:	*Patrick Allard*	France
Secretary General:	*Roberto Sulpizio*	Italy

Union Commissions and Working Groups

Union Commission on Climatic and Environmental Changes (CCEC)

Chair:	*Jianping Li*	China
Secretary:	*Tonie Van Dam*	Luxembourg

Union Commission on Mathematical Geophysics (CMG)

Chair:	*Alik Ismail-Zadeh*	Germany/Russia
Secretary:	*Ilya Zaliapin*	USA

Union Commission on Geophysical Risk and Sustainability (GRC)

Chair:	*John LaBrecque*	USA
Secretary General:	*Katia Kontar*	USA

Union Commission on Studies of Earth's Deep Interior (SEDI)

Chair:	*Christine Thomas*	Germany
Secretary:	*Michael Bergman*	USA

Union Commission on Planetary Sciences (UCPS)

Chair:	*Shuanggen Jin*	China
Secretary:	*Scot Rafkin*	USA

Union Commission on Data and Information (UCDI)

Chair:	*Sateesh Shenoi*	India
Secretary:	*Anatoly Soloviev*	Russia

International Association of Geodesy (IAG)

Markku Poutanen (Secretary General)

iag.office@nls.fi

Overview

The structure of IAG comprises a number of components: four Commissions, the Inter-Commission Committees on Theory (ICCT), Climate Research (ICCC), and Marine Geodesy (ICCM), Project Novel Sensors and Quantum Technology for Geodesy (QuGe), twelve International Scientific Services, the Global Geodetic Observing System (GGOS), and the Communication and Outreach Branch (COB).

The Commissions are divided into Sub-commissions, Study Groups and Working Groups. The Inter Commission Committees (ICCs) and the Project investigate scientific geodetic-related problems in close cooperation with the Commissions. The Services generate scientific products by means of Operation, Data and Analysis Centres.

The Global Geodetic Observing System GGOS is a component of IAG which works with the IAG Services to provide the geodetic infrastructure necessary for monitoring the Earth system and global change research. GGOS ensures the basis to maintain a stable, accurate and global reference frame, which is crucial for all Earth observation.

The COB provides communication, public information and outreach links, in particular via the IAG Website and the monthly Newsletters.

The IAG General Assembly, the Council, the Executive Committee, and the Office carry out the administration of IAG. The Council is composed by the delegates appointed by the national adhering bodies; the Bureau comprises the IAG President, Vice-President and Secretary General; the Executive Committee consists of 17 elected members; and the Office assists the Secretary General in fulfilling his duties. The COB is responsible for the promotional activities of the IAG and the communication with its members. The detailed programme of the IAG is published in the quadrennial Geodesist's Handbook, and reports are published in the bi-annual IAG Reports (Travaux de l'AIG).

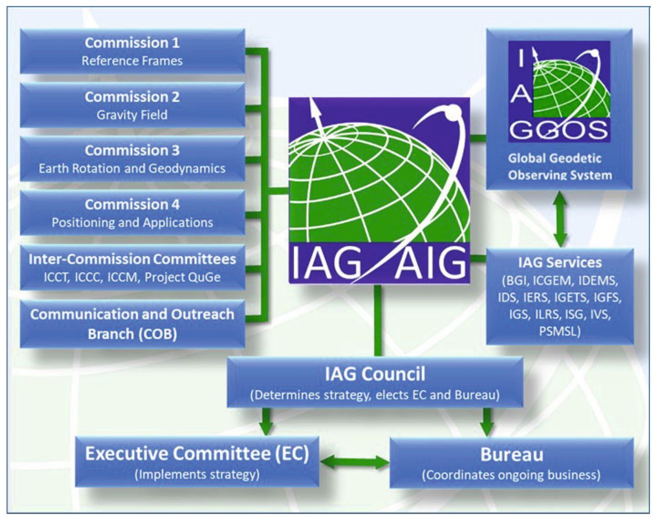


Figure 1. Structure of IAG

IAG Executive Committee

IAG Bureau

President:	*Zuheir Altamimi*	France
Vice-President:	*Richard Gross*	USA
Secretary General:	*Markku Poutanen*	Finland

IAG Immediate Past President

President 2015-2019:	*Harald Schuh*	Germany

IAG Immediate Past Secretary General

S.G. 2007-2019:	*Hermann Drewes*	Germany

IAG Commission Presidents

Commission 1:	*Christopher Kotsakis*	Greece
Commission 2:	*Adrian Jäggi*	Switzerland
Commission 3:	*Janusz Bogusz*	Poland
Commission 4:	*Allison Kealy*	Australia

Inter-Commission Committee on Theory (ICCT)

ICCT President:	*Pavel Novák*	Czech Republic

Global Geodetic Observing System (GGOS)

GGOS Chair:	*Basara Miyahara*	Japan

Communication & Outreach Branch (COB)

COB President:	*Szabolcs Rózsa*	Hungary

Representatives of the Services

Representatives:	*Johannes Böhm*	Austria
	Tom Herring	USA
	Toshimichi Otsubo	Japan

Members-at-Large

Members:	*Sonia Costa*	Brazil
	Yamin Dang	China

Non-voting Members

ICCC:	*Annette Eicker*	Germany
ICCM:	*Yuanxi Yang*	China
QuGe:	*Jürgen Müller*	Germany
IAG Past Presidents:	*Helmut Moritz*	Austria
	Ivan I. Mueller	USA
	Wolfgang Torge	Germany
	Fernando Sansó	Italy
	Gerhard Beutler	Switzerland
	Michael Sideris	Canada
	Chris Rizos	Australia
IAG Past SGs:	*Claude Boucher*	France

IAG Office

Finnish Geospatial Research Institute, National Land Survey of Finland, Masala, Finland

Director:	*Markku Poutanen*	Finland
Treasurer:	*Päivi Koponen*	Finland

IAG Communication & Outreach Branch

Budapest University of Technology and Economics

President:	*Szabolcs Rózsa*	Hungary
Newsletter Editor:	*Gyula Tóth*	Hungary

Journal of Geodesy

Editor in Chief:	*Jürgen Kusche*	Germany

IAG Symposia Series

Editor in Chief:	*Jeff Freymueller*	USA
Assistant Editor:	*Laura Sánchez*	Germany

IAG Commissions

Commission 1: Reference Frames

President:	*Christopher Kotsakis*	Greece
Vice-President	*Jean-Paul Boy*	France

Commission 2: Gravity Field

President:	*Adrian Jäggi*	Switzerland
Vice-President	*Mirko Reguzzoni*	Italy

Commission 3: Earth Rotation and Geodynamics

President:	*Janusz Bogusz*	Poland
Vice-President:	*Cheng-Li Huang*	China

Commission 4: Positioning and Applications

President:	*Allison Kealy*	Australia
Vice-President:	*Vassilis Gikas*	Greece

IAG Inter-Commission Committees

Inter-Commission Committee on Theory (ICCT)

ICCT President:	*Pavel Novák*	Czech Republic
Vice-President:	*Mattia Crespi*	Italy

Inter-Commission Committee for Climate Research (ICCC)

President:	*Annette Eicker*	Germany
Vice-President:	*Carmen Böning*	USA

Inter-Commission Committee on Marine Geodesy (ICCM)

President:	*Yuanxi Yang*	China
Vice-President:	*Heidrun Kopp*	Germany

Project Novel Sensors and Quantum Technology for Geodesy (QuGe)

President:	*Jürgen Müller*	Germany
Vice-President:	*Marcelo Santos*	Canada

IAG Global Geodetic Observing System

GGOS Chair:	*Basara Miyahara*	Japan
Vice-Chair:	*Laura Sanchez*	Germany

IAG Scientific Services

Bureau Gravimetrique International (BGI)
Director: *Sylvain Bonvalot* France

International Geodynamics and Earth Tide Service (IGETS)
Chair: *Hartmut Wziontek* Germany
Director Central Bureau: *Jean-Paul Boy* France

International Centre for Global Earth Models (ICGEM)
Director: *Elmas Sinem Ince* Germany

International Digital Elevation Model Service (IDEMS)
Director: *Kevin M. Kelly* USA

International DORIS Service (IDS):
Chair Governing Board: *Frank Lemoine* USA
Director Central Bureau: *Laurent Soudarin* France

International Earth Rotation and Reference Systems Service (IERS)
Chair of Directing Board: *Brian Luzum* USA
Director of Central Bureau: *Daniela Thaller* Germany

International Service for the Geoid (ISG)
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Director: *Daniela Carrion* Italy

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Chair: *Riccardo Barzaghi* Italy
Director of Central Bureau: *Georgios Vergos* Greece

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Chair of Governing Board: *Toshimichi Otsubo* Japan
Director of Central Bureau: *Michael Pearlman* USA

International Service for Geodesy and Astrometry (IVS)
Chair of Directing Board: *Axel Nothnagel* Austria
Director of Coord. Centre: *Dirk Behrend* USA

Permanent Service for Mean Sea Level (PSMSL)
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Fig. 1. First meeting of the IAG Executive Committee in Montreal 2019

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Commission 1 – Reference Frames

President: **Christopher Kotsakis** (Greece)
Vice President: **Jean-Paul Boy** (France)

http://www.com1.iag-aig.org

Terms of Reference

Reference systems and frames are of primary importance for Earth science based research and applications, satellite navigation and orbit determination as well as for practical applications in positioning, mapping and geo-information related fields. A precisely defined reference frame is needed for an improved understanding of the Earth system, including its rotation and gravity field, sea level change with time, tectonic plate motion and deformation, glacial isostatic adjustment, geocentre motion, deformation due to earthquakes, local subsidence, and other crustal displacements. Commission 1 activities and objectives deal with the theoretical and operational aspects of how best to define reference systems and how reference systems can be used for practical and scientific applications at different spatio-temporal scales on the deformable Earth. Commission 1 will closely interact with the other IAG Commissions and Services, the ICCT, the newly established ICCC, and the GGOS components where reference system aspects are of concern, to address related problems for the realization of celestial and terrestrial reference systems in conformity with present and future accuracy needs. Commission 1 is also linked with the IUGG/COSPAR joint Sub-Commission B2 (International Coordination of Space Techniques for Geodesy) under the aim to develop links and coordinate the work between various groups engaged in the field of space geodesy and geodynamics.

Objectives

The main objectives of Commission 1 are as listed in the IAG by-laws:

- Definition, establishment, maintenance and improvement of the geodetic reference frames;
- Advanced terrestrial and space observation technique development for the above purposes;
- International collaboration for the definition and deployment of networks of terrestrially-based space geodetic observatories;
- Theory and coordination of astrometric observation for reference frame purposes;
- Collaboration with space geodesy/reference frame related international services, agencies and organizations;
- Promote the definition and establishment of vertical reference systems at global level, considering the advances in the regional sub-commissions;
- Work to maintain a reference frame that is valuable for global change studies.

Structure

Sub-Commissions

SC 1.1: Coordination of Space Techniques
Chair: *Urs Hugentobler* (Germany)
SC 1.2: Global Reference Frames
Chair: *Xavier Collilieux* (France)
SC 1.3: Regional Reference Frames
Chair: *Carine Bruyninx* (Belgium)
SC 1.3a: Europe
Chair: *Martin Lidberg* (Sweden)
SC 1.3b: South and Central America
Chair: *Sonia Maria Alves Costa* (Brazil)
SC 1.3c: North America
Co-Chairs: *Michael Craymer* (Canada) and *Dan Roman* (USA)
SC 1.3d: Africa
Chair: *Elifuraha Saria* (Tanzania)

SC 1.3e: Asia-Pacific
Chair: *Basara Miyahara* (Japan)
SC 1.3f: Antarctica
Chair: *Martin Horwath* (Germany)
SC 1.4: Interaction of Celestial and Terrestrial Reference Frames
Chair: *Zinovy Malkin* (Russia)

Joint Study Groups

JSG T.32: High-rate GNSS (joint with ICCT, Commissions 3 and 4, GGOS; see description under ICCT)
Chair: *Mattia Crespi* (Italy)
JSG T.24: Integration and co-location of space geodetic observations (joint with ICCT, Commissions 3 and 4, GGOS; see description under ICCT)
Chair: *Krzysztof Sośnica* (Poland)
JSG T.31: Multi-GNSS theory and algorithms (joint with ICCT, Commission 4, GGOS; see description under ICCT)
Chair: *Amir Khodabandeh* (Australia)
JSG T.33: Time series analysis in geodesy (joint with ICCT, Commission 3, GGOS; see description under ICCT)
Chair: *Wieslaw Kosek* (Poland)
JSG T.29: Machine learning in geodesy (joint with ICCT, Commissions 2, 3 and 4, GGOS; see description under ICCT)
Chair: *Benedikt Soja* (USA)
JSG T.37: Theory and methods related to high-resolution digital topographic and bathymetric models (joint with ICCT, Commissions 2 and 3, GGOS; see description under ICCT)
Chair: *D.Carrion* (Italy)
JSG 3.1: Geodetic, seismic and geodynamic constraints on GIA (joint with Commissions 2 and 3, IASPEI; see description under Commission 3)
Chair: *Rebekka Steffen* (Sweden)
Vice-Chair: *Erik R. Ivins* (USA)

Joint Working Groups

JWG C.4: Regional sea level and vertical land motion (joint with ICCC, Commissions 2 and 4, GGOS; see description under ICCC)
Chair: *Roelof Rietbroek* (Germany)
GGOS Working Group: Towards a consistent set of parameters for a new GRS (joint with Commission 2, GGOS; see description under GGOS)
Chair: *Urs Marti* (Switzerland)

Program of Activities

Commission 1 fosters and encourages research in the areas of its sub-entities by facilitating the exchange of information and organizing symposia, either independently or at major conferences in geodesy, geophysics and geodynamics. Some events will be focused narrowly on the interests of the sub- commissions and other entities listed above, and others will have a broader commission-wide focus.

More specifically, the program of activities for Commission 1 includes:

- Theoretical and applied research activities related to reference frames;
- Research and development activities that impact the reference frame determination and its accuracy, as well as, the best and optimal usage of reference frames in Earth Science applications;
- Interaction with all established IAG Services: IVS, IGS, ILRS, IDS and the IERS, including their Combination Centres and Working Groups;
- Development in the theory of the transformation between Celestial and Terrestrial Reference Systems and application of the theory to improve the consistency between ICRF, ITRF and EOPs, in cooperation with IVS and IERS;
- Exploration of advanced methodologies for the combination of products and raw observations of space geodetic techniques;
- Investigation of systematic error sources and factors limiting the precision of space geodetic techniques and their combination;
- Encouraging and assisting regional sub-commission countries to re-define and modernize their national geodetic systems so that they are compatible with the ITRF;

The status of Commission 1, including its structure and membership, as well as links to the internet sites of its sub-entities and parent and sister organizations and services, will be updated regularly and can be viewed on the Commission's webpage.

Steering Committee

President Commission 1:	*Christopher Kotsakis* (Greece)
Vice President Comm. 1:	*Jean-Paul Boy* (France)
Chair Sub-Comm. 1.1:	*Urs Hugentobler* (Germany)
Chair Sub-Comm. 1.2:	*Xavier Collilieux* (France)
Chair Sub-Comm. 1.3:	*Carine Bruyninx* (Belgium)
Chair Sub-Comm. 1.4:	*Zinovy Malkin* (Russia)
Representative of IGS:	*Paul Rebischung* (France)
Representative of IERS:	*Detlef Angermann* (Germany)
Member-at-Large:	*Guangli Wang* (China)

Sub-Commissions

SC 1.1: Coordination of Space Techniques

Chair: *Urs Hugentobler* (Germany)

Terms of Reference

Space techniques play a fundamental role for the realization and dissemination of highly accurate and long term stable terrestrial and celestial reference frames as well as for accurate monitoring of the Earth orientation parameters linking the two fundamental frames. The current space geodetic techniques contributing to ITRF and ICRF, i.e., Very Long Baseline Interferometry (VLBI), Satellite and Lunar Laser Ranging (SLR/LLR), Global Navigation Satellite Systems (GNSS) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) have particular strengths and technique-specific weaknesses.

Strengths of the techniques are exploited by combining them making use of fundamental sites co-locating more than one technique. Sub-commission 1.1 focusses on the coordination of research related to the geodetic space techniques with emphasis on co-location aspects at fundamental geodetic observatories as well as on co- location targets in space, considering common parameters such as coordinates of stations and satellites, troposphere parameters, and clock parameters.

Objectives

- Coordinate research on co-location using common parameters in space;
- Coordinate research on co-location using common parameters at fundamental geodetic observatories;
- Explore the use of new techniques and technologies;
- Interface with IERS WG on Site Survey and Co- location;
- Interface with the GGOS Committee on Performance Simulations and Architectural Trade-Offs (PLATO);
- Interface with Joint WG on Tropospheric Ties.

Working Groups of Sub-Commission 1.1

JWG 1.1.1: Intra- and Inter-Technique Atmospheric Ties (joint with SC 4.3 and GGOS)

Chair: *Kyriakos Balidakis* (Germany)
Vice-Chair: *Daniela Thaller* (Germany)

Terms of Reference

The differences between atmospheric parameters (mainly zenith delays and gradients) at co-located stations that observe nearly simultaneously, and stem from external systems (e.g., meteorological sensors or weather models) are understood as atmospheric ties. Atmospheric ties mainly exist because of differences in (i) the observing frequency, (ii) the relative position, and (iii) the observing system set-up.

The acquisition of accurate atmospheric delay corrections is of paramount importance for mm-level positioning employing space geodetic techniques. Atmospheric delay corrections may stem from dedicated instruments such as water vapor radiometers, meteorological sensors, numerical weather models, or from the geodetic data itself. While the latter is fairly common for modern GNSS and VLBI, observation geometry and accuracy limitations inherent to other systems such as SLR and DORIS impede the accurate atmospheric parameter estimation, thus hindering among else positioning. To this end, it might be useful to compare and combine atmospheric parameters at co-located sites, in a manner similar to the combination of station and satellite coordinates, as well as Earth rotation parameters (via local, space, and global ties, respectively). The multi-technique combination is indispensable to the distinction between real signals and undesired technique-specific artefacts. Nowadays, the multi-technique combination is facilitated by the increasing investments in state-of-the-art geodetic infrastructure at co-located sites. However, a host of systematic and random errors render the combination via atmospheric ties a difficult task. Moreover, since atmospheric delays are dependent upon essential climate variables (pressure, temperature, and water vapor), differences in long-term atmospheric delay time derivatives at co-located stations might offer an insight into local climate change.

Objectives

The purpose of this working group is to answer the following questions:

- How can one relate atmospheric (electrically neutral) parameter estimates and the time derivatives thereof that refer to different place, time, and observing system? What are the limits in distance, time lag, and observing system?

- What is the optimal way to combine atmospheric parameters?
- What is the benefit from including atmospheric ties in a multi-technique terrestrial reference frame combination?

Proposed activities

- Comparison of atmospheric (electrically neutral) delay estimates from single-technique geodetic analysis (GNSS, SLR, VLBI, and DORIS).
- Comparison of atmospheric delays from state-of-the-art meso-β scale weather models (e.g., ERA5 and MERRA2), and high-resolution runs utilizing the Weather Research and Forecasting (WRF) Model.
- Assessment of spatial and temporal correlation between atmospheric parameters.
- Assessment of multi-technique combination employing atmospheric ties on the single site and global TRF level.

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Thaller, Daniela (Germany), Vice-Chair
Wang, Xiaoya (China)
Wijaya, Dudy (Indonesia)
Zus, Florian (Germany)

SC 1.2: Global Reference Frames

Chair: *Xavier Collilieux* (France)

Terms of Reference

Sub-commission 1.2 focuses its activity on the definition and realization of the terrestrial reference system (TRS). The TRS realization, named Terrestrial Reference Frame (TRF), is fundamental to study and locate global phenomena or objects at the Earth's surface, in the ocean or in space. It is used as the basis of several operational observation system processing chains such as sea level determination from space and Earth's rotation monitoring but is also used for most regional and national TRFs. Thus, TRF specifications in terms of origin, scale and orientation have to be optimally realized to satisfy user needs. That's why sub-commission 1.2 shall study either fundamental questions or more practical aspects that could improve current TRF determinations.

Thanks to the accumulation of space geodesy observations and progress in modeling and analysis, non-stationary Earth surface displacements are nowadays clearly evidenced. The next generation of TRF should be able to explicitly model them or should be constructed in such a way that those displacements are accurately modelled. There are currently two different approaches to represent the TRF: Long-term linear and nonlinear TRFs. Time series of quasi-instantaneous frames are proposed but practical implementations still need to be investigated so that the implicit reference frame definition reach the required accuracy. Augmented parametric TRF, coupled with enhanced forward displacement models is an alternative to TRF time series. This approach is in agreement with past modeling of the International Terrestrial Reference Frame (ITRF) but still require progress in forward models (e.g. loading and post-seismic deformations). The dominant non-steady displacement signal is the geocenter motion which is related to the origin definition of the frame. While its main contribution is included in non-tidal loading forward models and while it can be observed by space geodesy, there are still open questions regarding its annual variation.

Technique systematic errors still exist in space geodesy products, which impact the TRF definition, especially the scale parameter. Dedicated satellite missions with onboard multi-technique sensors could improve further our understanding of technique systematic errors thanks to solving parameters common to multiple techniques. However, a set of accurate tie vectors that relate position of various technique instruments at co-location sites will still be of outmost importance to validate those new space-ties and monitor their long-term variations. In parallel, due to the high cost of local tie surveys, it is worth investigating supplementary ways to monitor reference point variations with time. Here, the potential of PSInSAR technique to investigate ground/monument deformation is proposed.

A step forward could be established by investigating relativistic reference frames based on a network of clocks in space linked with time transfer technologies. Such realized frame would be entirely decoupled from ground fixed stations and could be used to reference any point on the Earth's surface. The relativistic frequency shift between clocks in space and on the ground would be a direct measurement of the Earth gravity potential. This technology can be used to realize a world height system based on a network of ground clocks.

While this ultimate goal still requires intensive research works, TRF and future World Height Systems need to be studied in closer partnership in order to connect reference benchmarks, gravimeters or clocks to the TRF but also to provide consistent coordinate and height time-variations.

The work of this sub-commission will be done in partnership with the International Earth Rotation and Reference Systems Service (IERS) as well as IAG Global Geodetic Observing System (GGOS).

Objectives

The main objectives of sub-commission 1.2 are the following:

- Definition of the global terrestrial reference frame (origin, scale and orientation, time evolution, standards, conventions, models);
- Methods to determine local tie vectors and to relate instrument reference points to surveyed ground markers;
- Investigate new methods to determine relative motions at co-location sites;
- Evaluation of technique systematic errors by focusing on errors at co-location sites;
- Enhanced forward modeling of the Earth's surface deformation;
- Modeling of the reference frame in general relativity;
- Linking global height reference frames with the terrestrial reference frame;
- Pursue studies and investigation related to multi-technique satellites (space ties) and concepts of novel dedicated missions with onboard multi-technique sensors.

Link to Services

Sub-Commission 1.2 will establish close links to relevant services for geodetic reference frames, namely the IERS, GGOS and IAG technique services: International GPS Service (IGS), International Laser Ranging Service (ILRS), International VLBI Service for Geodesy and Astrometry (IVS), and International DORIS Service (IDS). A close link with the IERS Conventions Center will be also maintained, especially for chapter 4 ("Terrestrial Reference Systems and Frames") updates.

Working Groups of Sub-Commission 1.2

WG 1.2.1: Assessing impacts of loading on Reference Frame realizations

Chair: *Anthony Mémin* (France)

Terms of Reference

Non-tidal loading (NTL) deforms the Earth's surface adding variability to the coordinates of geodetic sites. The effects of NTL are already observed in geodetic time series from VLBI, SLR, DORIS and GNSS techniques. They occur in a wide range of period, from sub-daily to centennial time scale. They also have an impact on crustal velocity estimates and as a consequence on the realization of the terrestrial reference frame.

It has been shown that unconsidered NTL effects can bias estimates of geodetic vertical velocity by 0.5 mm/yr over the continent to more than 1 mm/yr in the southern tropical regions between 1993 and 2014 (Santamaría-Gómez and Mémin 2015). It is five to more than ten times larger than the requirement of the Global Geodetic Observing System on interannual to secular time scales and about one-third of the current rate of sea level rise.

Geodetic techniques require accurate global circulation models to allow precise estimation of the Earth's surface displacements to reduce the variability of position time series, in addition to the corresponding time-variable gravity field affecting the orbits of artificial satellites. Correcting for NTL at the observation level reduced for example the variability of GNSS time series by up to 7 mm (Männel et al. 2019).

According to the 2010 IERS conventions, there are currently no recommended surface-mass change models (atmosphere, ocean circulation, ocean response to atmospheric changes, hydrology, past- and present-day ice-mass, sea level) nor Earth models (1D vs 3D, elastic, visco-elastic, rheology, coastline definition) to account for NTL deformation in geodetic position time series. Hence, a better understanding of NTL contribution to geodetic time series is required. Also, several studies have already shown that a posteriori corrections slightly decrease the variance factor of a Terrestrial Reference Frame (TRF) multi-technique combination but the improvement at some sites was also counterbalanced by degradation at others. The accuracy and precision of current space geodetic techniques are such that several scientific studies have already considered atmospheric loading corrections at the observation level. However, there still exist open questions regarding the application of loading corrections for the generation of operational geodetic products, either a priori or a posteriori.

References

Santamaría-Gómez A, Mémin A (2015) Geodetic secular velocity errors due to interannual surface loading deformation. Geophys J Int Exp Lett 202 (2):763–767, doi:10.1093/gji/ggv190.

Männel B, Dobslaw H, Dill R, Glaser S, Balidakis K, Thomas M, Schuh H (2019) Correcting surface loading at the observation level: impact on global GNSS and VLBI station networks, J Geod, doi.org/10.1007/s00190-019-01298-y.

Objective

The principal objectives of the scientific work are to assess the effects of load and Earth models and their applications for TRF utilization and to assemble specific recommendations for users and future IERS conventions.

Program of Activities

- Create and maintain an updated list of loading studies: models and observations.
- Compare and assess differences between existing load models.
- Assess ice and sea level change loading deformation.
- Assess the propagation of loading model errors and differences in using several Earth models into the site coordinates, TRF parameters and the ITRF.
- Determine whether load models should be applied a priori or a posteriori.
- Organize meetings during international conferences (EGU, AGU…).
- Suggest recommendations for IERS conventions.

List of members

Jean-Paul Boy (France)
Kristel Chanard (France)
Benjamin Maennel (Germany)
Anthony Mémin (France), Chair
Laurent Métivier (France)
Manuela Seitz (Germany)
Giorgio Spada (Italy)
Daniela Thaller (Germany)
Wouter van der Wal (The Netherlands)

Corresponding members
Christopher Kotsakis (Greece)

JWG 1.2.2: Methodology for surveying geodetic instrument reference points
(joint with IERS)

Chair: *Ryan Hippenstiel* (USA)
Vice-Chair: *Sten Bergstrand* (France)

Terms of Reference

The International Terrestrial Reference System is built upon multiple geodetic techniques; Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), Doppler Orbitography and Radiopositioning Integrated by satellite (DORIS), and Global Navigation Satellite Systems (GNSS). At locations where these techniques are co-located, it is vital to determine and understand the vectors between the reference points of each technique. These vectors are determined by local tie surveys conducted terrestrially with various procedures and geodetic instruments. The reference points should be collected and properly aligned to a global reference frame in order to produce relative and absolute coordinates.

As the science of local tie surveys has developed, so has technology and the expectation of higher precision and improved protocols. It is the desire of this working group to investigate the current and expected best practices available, along with documenting past efforts, both in the field and researched. This working group will share methodology of existing tie surveys, continued to develop and document recommended procedures, and also archive surveys completed by all agencies represented.

In addition, efforts will be made to isolate systematic errors of the space geodetic techniques using surveying methods and investigate field procedures that could be completed during the course of a tie survey in order to provide the operator valuable feedback on potential physical errors found onsite. One critical example of this is quantifying thermal and gravitational deformation in VLBI sensors. It is the overall goal of the working group to encourage consistent field practice, terminology, and documentation throughout the community, with a continued eye on the future of tie surveys.

Objective

Enhance and improve knowledge of local tie surveys through applied field practice, research, and dissemination of materials developed.

Activities

- Investigate thermal and gravitational deformation.
- Consider importance and inclusion of DoV observations.

- Discuss overall error budget and precision (achieved/necessary) considering the above.
- Continue to enhance guidelines on procedures (and subsequent feedback for improvement).
- Archive reports, tie vectors and raw data of all agencies conducting tie surveys.
- Gather, distribute, and maintain publications on related matters.
- Coordinate with and solicit feedback from all geodetic techniques on developments.

Expectations

- Participation in local tie surveys and/or testing of new methodologies.
- Attendance of meetings or participation in remote/virtual discussions.
- Reporting of survey results and/or research efforts towards the objectives of the WG.
- Develop and maintain a depository of past and future reference materials.

List of members

Zuheir Altamimi (France)
Sten Bergstrand (France), Vice-Chair
Steven Breidenbach (USA)
Benjamin Erickson (USA)
Kendall Fancher (USA)
Charles Geoghegan (USA)
Ryan Hippenstiel (USA), Chair
Kevin Jordan (USA)
Jack McCubbine (Australia)
Damien Pesce (France)
Jerome Saunier (France)

Corresponding members
Xavier Collilieux (France)
Mike Pearlman (USA)

JWG 1.2.3: Toward reconciling Geocenter Motion estimates

(joint with IERS)

Chair: *Kristel Chanard* (France)
Vice-Chair: *Alexandre Couhert* (France)

Terms of Reference

The International Terrestrial Reference Frame (ITRF) origin is realized through Satellite Laser Ranging (SLR) orbit dynamics determining the Center of Mass (CM) of the Earth system, e.g. the solid Earth and its fluid envelops. The ITRF origin is considered, over secular time scales, to be the mean Earth CM, averaged over the time span of SLR observations (IERS Conventions 2010). Over shorter time scales, the ITRF origin behaves as an approximated Center of Figure (CF) of the solid Earth surface. The motion of CM with respect to CF is commonly called geocenter motion.

For number of operational and scientific applications, such as improving the ITRF accuracy or refining estimates of sea level variations, the ITRF origin should coincide with CM at any time. Thus, accessing true geocentric positions requires, to this day, to adopt a model for geocenter motion. However, due to discrepancies in models derived from various techniques and methods, no conventional model for geocenter motion has not been conventionally accepted yet. It is therefore the focus of this working group to identify scientific and technical obstacles leading to inconsistencies in geocenter motion estimates obtained from various geodetic techniques or forward geophysical models. Consequently, the working group will first gather geocenter motion time series derived from geodetic products, along with detailed information on methods of estimation, compare estimates and closely investigate discrepancies. We seek to identify potential sources of geodetic systematic errors and/or inconsistencies in methodologies used to retrieve geocenter motion (network effect, etc.), at both the annual and interannual time periods. A special attention will then be given to improving and/or developing new methods, less sensitive to errors in geodetic products and provide refined geocenter motion estimates.

Objectives

- To review all methods to estimate geocenter motion, both from geodetic data and forward geophysical modelling, and systematically compare results.
- To focus on discrepancies in geocenter motion estimates and investigate potential biases in methods and/or systematic errors in geodetic products.
- To study the relative merit of geocenter motion data types (SLR, DORIS, GNSS, GNSS+LEOs). Special

emphasis should be placed in evaluating the network-effect biases.
- To evaluate consistencies in methods used to retrieve geocenter motion (translational and inverse approaches, forward modelling).
- To assess the impact of errors in geocenter motion through variability in estimates for operational and scientific users.

Program of Activities

- Organize a group meeting to discuss the above objectives.
- Gather estimates of geocenter motion from working group members and proceed to systematic comparison highlighting discrepancies.
- Publishing a report on the current status of geocenter motion and associated error budget (and possibly provide common components to all estimates as a mean geocenter motion model).
- Contribution to international meetings and conferences (AGU, EGU, IUGG).
- Managing a website with all geocenter motion models and detailed information on estimates.
- Common publications by working group members.

List of members

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Xavier Collilieux (France)
Alexandre Couhert (France), Vice-Chair
Robert Dill (Germany)
Suzanne Glaser (Germany)
Christopher Kotsakis (Greece)
Flavien Mercier (France)
Laurent Métivier (France)
Paul Rebischung (France)
John Ries (USA)
Ricardo Riva (Nehterlands)
Krystof Sosnica (Poland)
Dariusz Strugarek (Poland)
Xiaoping Wu (USA)
Radoslaw Zajdel (Poland)

Study Groups of Sub-Commission 1.2

SG 1.2.1: Relevance of PSInSAR analyses at ITRF co-location sites

Chair: *Xavier Collilieux* (France)
Vice-Chair: *Thomas Fuhrmann* (Australia)

Terms of Reference

The scientific community has recognized the need for a highly accurate terrestrial reference frame (TRF) for Earth Science applications. Current determination of the International Terrestrial Reference System is made by combining data from space geodetic techniques, namely Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), Doppler Orbitography and Radiopositioning Integrated by satellite (DORIS), Global Navigation Satellite Systems (GNSS), but also terrestrial measurements from local tie survey at co-location sites. For most of the sites, such local tie surveys are not performed on a regular basis. Thus, it is not possible to test the assumption of no relative motion between instrument reference points which is currently done almost exclusively by analyzing space geodetic data themselves.
The PSInSAR (Persistent Scatterer Interferometric Synthetic Aperture Radar) technique allows for determining deformation maps over large areas with various spatial resolutions as function of the satellite missions. Due to the availability of freely available SAR data for a significant period of time at many sites, it is relevant to ask if such data could supplement local tie measurements for those sites where sufficiently repeated terrestrial surveys do not exist. There are however some limitations that need to be addressed such as the size of a co-location site which is between 100 m and 1 km or the reference points themselves that are not accessible from the SAR satellites. Artificial corner reflectors or active transponders might however be used to add a PSInSAR measurement point in this context. Studying PSInSAR results in C- and X-band at some co-location sites is worth investigating to assess the potential use of this technique in reference frame determination in the future.

Objective

The main objective is to investigate if the PSInSAR technique can be used to supplement local tie surveys at ITRF multi-technique sites.

Proposed activities

- List strength and weakness of the PSInSAR technique for this application.
- Collect all studies related to INSAR and more particularly PSInSAR at co-location sites.
- If relevant, make an inventory of SAR images (for all missions) available at ITRF co-location sites.
- If relevant, identify multi-technique co-location sites where PSInSAR processing should be performed and compare InSAR results from various software packages. Compare results of free, but low-resolution, Sentinel-1 data with commercial high-resolution data (e.g. TerraSAR-X) where available; investigate whether a request for a supersite could be used to obtain additional high-resolution data (https://www.earthobservations.org/documents/gsnl/20120918_GSNL_CEOSSelectionProcess.pdf).
- Investigate the relevance of installing corner reflectors or transponders at co-location sites.
- Report conclusions and recommendations in IAG 2021 and/or IUGG2023 proceedings.

List of members

Xavier Collilieux (France), Chair
Francesco DeZan (Germany)
Stefan Friedländer (Germany)
Thomas Fuhrmann (Australia)
Christoph Gisinger (Germany)
Thomas Gruber (Germany)
Amy Parker (Australia)

Corresponding members
Ann Chen (USA)
Clément Courde (France)

SC 1.3: Regional Reference Frames

Chair: *Carine Bruyninx* (Belgium)

Terms of Reference

Sub-commission 1.3 deals with the definitions and realizations of regional reference frames and their connection to the global International Terrestrial Reference Frame (ITRF) and International Height Reference Frame (IHRF). It offers a home for service-like activities addressing theoretical and technical key common issues of interest to regional organisations.

Objectives

In addition to the specific objectives of each regional Sub-commission, the main objectives of SC1.3 as a whole are to:

- Coordinate the activities of the regional Sub-commissions focusing on exchange of data, competences and results;
- Promote operation of permanent GNSS stations, in connection with IGS whenever appropriate, as the basis for the long-term maintenance of regional reference frames;
- Promote open access to the GNSS data from permanent GNSS stations used for the maintenance of regional reference frames and scientific applications;
- Develop specifications for the definition and realization of regional reference frames, including the vertical component;
- Encourage and stimulate the development of the AFREF project in close cooperation with IGS and other interested organizations;
- Encourage and assist countries, within each regional Sub-commission, to re-define and modernize their national geodetic systems, compatible with the ITRF;
- Support the efforts of the United Nations Initiative on Global Geospatial Information Management (UN-GGIM) towards a sustainable Global Geodetic Reference Frame (GGRF).

Program of Activities

- Provide a forum for addressing activities, results and key issues of common interest to the regional Sub-commissions;
- Develop analysis strategies and compare methods for the implementation of the regional reference frames and their expression in the ITRF, in full interaction with the IGS;
- Consider developing tectonic deformation models that will enable transformation of locations within a defined reference frame between different epochs;

SC 1.3a: Europe (EUREF)

Chair: *Martin Lidberg* (Sweden)
Secretary: *Karin Kollo* (Estonia)

Terms of Reference

EUREF, the Regional Reference Frame Sub-commission for Europe, deals with the definition, realization and maintenance of the European Reference Frames. EUREF is focusing on both the spatial and the vertical components in close cooperation with the pertinent IAG components (Services, Commissions, and Inter-commission projects). For more information, see www.euref.eu.

Objectives

- The definition, realization and maintenance of the European Geodetic Reference Systems;
- The promotion and assistance of the adoption and use of European Terrestrial Reference System (ETRS89) and European Vertical Reference System (EVRS) in our partner countries;
- The development and maintenance of the EUREF GNSS Permanent Network (EPN) which is the ground based GNSS infrastructure for scientific and practical applications in positioning and navigation (Global Geodetic Observing System - GGOS, IGS Real-time Service);
- The development of strategies and technologies for the realization of geodetic reference systems.

Structure

EUREF is composed of representatives from European IAG member countries. The Governing Board (GB) is composed of members elected by the EUREF plenary, members in charge of special tasks and ex-officio members. The current Chair of GB is *Wolfgang Söhne* (Germany).

In addition, several Working Groups have been set up:

- Working group on "European Dense Velocities"
  Chair: *Elmar Brockmann* (Switzerland)
- Working group on "EPN Densification"
  Chair: *Ambrus Kenyeres* (Hungary)
- Working group on "Deformation models"
  Chair: *Martin Lidberg* (Sweden)
- Working Group on "Multi GNSS"
  Chair: *Elmar Brockmann* (Switzerland)
- Working group on "EPN Reprocessing"
  Chair: *Christof Völksen* (Germany)

Program of Activities

- Continue to develop the EPN in close cooperation with IGS (International GNSS Service), for the maintenance of the European Terrestrial Reference Frame (ETRF), as a contribution to the ITRF and as an infrastructure to support practical applications for precise positioning and referencing geo-information;
- Extend the Unified European Levelling Network (UELN) in order to include as many countries as possible in the current realization of the European Vertical Reference System (EVRS), and further continue the long-term maintenance of the European Vertical Reference Frame (EVRF) applying a kinematic approach;
- Closely follow and contribute to the developments regarding the International Height Reference System (IHRS) and its realizations in International Height Reference Frames (IHRF), and when appropriate establish the precise relation between IHRF and EVRF;
- Promote efforts on regional geoid models in Europe as the link between the ETRF and the EVRF;
- Support new developments in reference frame realization and applications by introducing new technologies like real-time GNSS data transfer and products, as well as Galileo for precise positioning;
- Realize a dense and homogeneous position and velocity product for Europe;
- Establish a dense velocity field model in Europe for the long-term maintenance of the European reference frame;
- Provide GNSS tropospheric estimates at the EPN stations in support of climate research;
- Contribute to the IAG Programme GGOS using the installed infrastructures managed by the EUREF members;
- Promote the adoption of the reference systems defined by EUREF (ETRS89 - European Terrestrial Reference System 1989 and EVRS - European Vertical Reference System) in the European countries and European-wide initiatives related to geo-referencing activities like INSPIRE;
- Cooperate with European political and scientific organisations and projects, e.g. EuroGeographics, EUMETNET, CEGRN (Central European GPS Geodynamic Reference Network), EPOS (European Plate Observing System), UN-GGIM: Europe, etc.;
- Organize annual symposia addressing activities carried out at national and Europe-wide levels related to the global work and objectives of EUREF.

Members of the EUREF Governing Board

The members of the Governing Board in the fall of 2019 are as follows. However, some new members are foreseen to be elected at the symposium in May 2021. An up to date list is available at www.euref.eu.

Carine Bruyninx (Belgium)
Elmar Brockmann (Switzerland)
Rolf Dach (Switzerland)
Ambrus Kenyeres (Hungary)
Karin Kollo (Estonia)
Juliette Legrand (Belgium)
Martin Lidberg (Sweden)
Tomasz Liwosz (Poland)
Rosa Pacione (Italy)
Martina Sacher (Germany)
Wolfgang Söhne (Germany, Chair of GB)
Christof Völksen (Germany)

Active honorary members:
Zuheir Altamimi (France)
Alessandro Caporali (Italy)
Markku Poutanen (Finland)
João Agria Torres (Portugal)

SC 1.3b: South and Central America (SIRGAS)

Chair: *José Antonio Tarrio* (SIRGAS WG I Chair)
Vice-Chair: *Demián Gomez* (SIRGAS WG II Chair)

Terms of Reference

Sub-commission 1.3b (South and Central America) encompasses the activities developed by the "Geocentric Reference System for the Americas" (SIRGAS). As such, it is concerned with the definition, realization and maintenance of a modern geodetic reference infrastructure for South and Central America and the Caribbean. This includes a geometric reference frame consistent with ITRS/ITRF and a gravity field-related vertical reference system, defined and realized globally.

Objectives

- To determine, maintain and make available a geocentric reference frame (a set of stations with high-precise geocentric positions and their variation with time) as a regional densification of the global ITRF;
- To support the SIRGAS countries in the establishment and maintenance of national geodetic reference networks as local densifications of SIRGAS in order to guarantee accessibility to the global ITRF at national and local levels;
- To establish a unified vertical reference system supporting the determination and precise combination of physical and geometric heights as well as their variations with time;
- To contribute to the GGOS program by developing and implementing state-of-the-art products based on the SIRGAS observational infrastructure;
- To promote, support, and coordinate the efforts of the Latin American and Caribbean countries to achieve these objectives.

Structure

The structure of the Sub-commission 1.3b is based on the functioning SIRGAS Working Group I - Reference System and Working Group II - National Level. SIRGAS WG I coordinates the functioning and analysis of the SIRGAS Continuously Operating Network (SIRGAS-CON). SIRGAS WGI also promotes the installation of the of analysis centres for SIRGAS, under the responsibility of American institutions and the use of SIRGAS observations for atmospheric (ionosphere and troposphere) studies. SIRGAS WGII is responsible for promoting and supporting the adoption of SIRGAS realization through continuous operating GNSS stations.

- SC1.3b-WG 1: Reference System
  Chair: José Antonio Tarrio (Chile)
- SC1.3b-WG 2: SIRGAS at National Level
  Chair: Demián Gomez (US)

The SIRGAS Executive Committee (as it is named in the SIRGAS statutes) is composed of:
- Chair: *Sonia María Alves Costa* (Brasil).
- Vice-Chair: *Diego Alejandro Piñón* (Argentina)
- WG1 Chair: *José Antonio Tarrio* (Chile)
- WG2 Chair: *Demián Gomez* (US)
- WG3 Chair: *Gabriel do Nascimento Guimarães* (Brazil)

Program of Activities

Since the SIRGAS countries are improving their national reference frames by installing an increasing number of continuously operating GNSS stations, it is necessary to outline the best strategy for the appropriate integration of those frames into the continental frame. This includes:
- Promotion of the IGS and IERS standards within the SIRGAS countries to ensure the adequate installation, maintenance, and analysis of continuously operating GNSS stations;
- Establishment of a SIRGAS National Processing Centre in all the member countries;
- Refinement of the SIRGAS station hierarchy. At present, two classes are considered: core and densification stations (the establishment of other categories is under consideration);
- Promotion of the adequate usage of SIRGAS as a reference frame by means of capacity building activities. This comprises SIRGAS schools on reference frames, scientific processing of GNSS data, atmospheric analysis based on the SIRGAS infrastructure, etc.;
- Promotion and implementation of real-time services based on the SIRGAS infrastructure to make available the reference frame to more users;
- The kinematics of the SIRGAS frame, up to now, have been represented by linear station movements (i.e. constant velocities). This representation is not sufficiently precise due to existing seasonal variations in the station position time series and due to discontinuities caused by the frequent occurrence of seismic events in the SIRGAS region.

According to this, it is necessary:

- To model non-linear station movements within the reference frame computation;
- To implement a methodology aiming at a precise transformation between different epochs and, in general, between pre-seismic and post-seismic reference frame realizations in particular;
- To evaluate the feasibility of computing and using near-real time reference frames instead of those based on epoch station positions and constant velocities.

The establishment of a unified vertical reference system continues to be a big challenge of SIRGAS. The related activities concentrate on:

- Continental adjustment of the national vertical networks in terms of geo-potential numbers;
- Combined analysis of tide gauge registrations, GNSS positioning and satellite altimetry observations to determine the dynamic ocean topography at the classical vertical datums;
- Determination of potential differences between the reference tide gauges and the global reference surface;
- Stronger cooperation with the Sub-Commission 2.4b (Gravity and Geoid in South and Central America - GGSCA) to promote national initiatives regarding the modernization of the gravity reference networks and the computation of geoid models of high resolution.

Hourly SIRGAS ionospheric models (vTEC) based on the GNSS SIRGAS stations have been generated since 2003 to 2015. The SIRGAS ionospheric model is being upgraded to include a better distribution of the electron density based on the assimilation of ground- and space-based GNSS observations. In addition, SIRGAS is developing a service for estimate hourly tropospheric Zenith Total Delay (ZTD) based on the operational SIRGAS processing. The ZTD estimates allow inferring Integrated Water Vapour (IWV) values with high accuracy.

Members

SIRGAS Executive committee

Sonia María Alves Costa, Chair (Brasil)
Diego Alejandro Piñón, Vice-Chair (Argentina)
José Antonio Tarrio SIRGAS-WG1 Chair (Chile)
Demián Gomez SIRGAS-WG2 Chair (US)
Gabriel do Nascimento Guimarães SIRGAS-WG3 Chair (Brazil)

SIRGAS Directing council

Hermann Drewes, Representative of IAG
Hector Carlos Rovera Di Landro, Representative of PAIGH
Juan Francisco Moirano (Argentina)
Demian Gómez (Argentina)
Arturo Echalar Rivera (Bolivia)
Mario Sandoval Nava (Bolivia)
Luiz Paulo Souto Fortes (Brazil)
Sonia Maria Alves Costa (Brazil)
Emilio Aleuy Schwerter (Chile)
Sergio Rozas Bornes (Chile)
Jose Ricardo Guevara Lima (Colombia)
Francisco Javier Mora Torres (Colombia)
Max Lobo Hernández (Costa Rica)
Álvaro Álvarez Calderón (Costa Rica)
Bolívar Troncoso Morales (Dominican Republic)
José Leandro Santos (Dominican Republic)
Edgar Fernando Parra Cárdenas (Ecuador)
Jose Luis Carrión (Ecuador)
Carlos Enrique Figueroa (El Salvador)
Wilfredo Amaya Zelaya (El Salvador)
Óscar Cruz Ramos (Guatemala)
Fernando Oroxan Sandoval (Guatemala)
Rene Duesbury (Guyana)
Hilton Cheong (Guyana)
Bruno Garayt (French Guyana)
Alain Harmel (French Guyana)
Luis Alberto Cruz (Honduras)
Enrique Muñoz Goncen (Mexico)
Francisco Medina (Mexico)
Wilmer Medrano Silva (Nicaragua)
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Javier Cornejo (Panama)
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Daniel R. Roman (USA)
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SIRGAS Scientific Council

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Luiz Paulo Souto Fortes (Brazil)
Laura Sanchez (Germany)
Claudio Brunini (Argentina)
María Virginia Mackern (Argentina)

SC1.3c: North America (NAREF)

Co-Chairs: *Michael Craymer* (Canada)
Dan Roman (USA)

Terms of Reference

To provide international focus and cooperation for issues involving the horizontal, vertical, and three-dimensional geodetic control networks of North America, including Central America, the Caribbean and Greenland (Denmark). For more information, see www.naref.org.

Objectives

In collaboration with the IAG community, its service organisations, and the national geodetic organizations of North America, the aims and objectives of this regional Sub-commission are to provide international focus and cooperation for issues involving the horizontal, vertical and three dimensional geodetic control networks of North America. Some of these issues include:

- Densification of the ITRF reference frame in North America and the promotion of its use;
- Definition, maintenance and future evolution of plate-fixed geometric reference frames for North America, including the North American Datum of 1983 (NAD83) and the forthcoming North American Terrestrial Reference Frame of 2022 (NATRF2022).
- Effects of crustal motion, including post-glacial rebound and tectonic motions along, e.g., the western coast of North America and in the Caribbean;
- Standards for the accuracy of geodetic positions;
- Coordination of efforts with neighbouring SC1.3b South America (SIRGAS) to ensure strong ties between each other's reference frames;
- Outreach to the general public through focused symposia, articles, workshops and lectures, and technology transfer to other groups.

Steering committee

Michael Craymer (Canada)
Dan Roman (USA)
Finn Bo Madsen (Denmark)

Working Groups of Sub-Commission 1.3c

WG 1.3c.1: North American Reference Frame Densification (NAREF)

Chair: *Michael Craymer* (Canada)

Programme of Activities

To densify the ITRF reference frame in the North American region by organizing the computation of weekly coordinate solutions and associated accuracy information for continuously operating GPS stations that are not part of the current IGS global network. A cumulative solution of coordinate and velocities will also be determined on a weekly basis. The working group will organize, collect, analyse and combine solutions from individual agencies, and archive and disseminate the weekly and cumulative solutions.

Members

Michael Craymer (Canada), Chair
Mike Piraszewski (Canada)
Remi Ferland (Canada)
Daniel Roman (USA)
Theresa Damiami (USA)
Sungpil Yoon (USA)
Jarir Saleh (USA)
Finn Bo Madsen (Denmark)

WG 1.3c.2: Plate-Fixed North American Terrestrial Reference Frame of 2022 (NATRF2022)

Chair: *Dan Roman* (USA)

Programme of Activities

To establish a high-accuracy, geocentric reference frame, including velocity models, procedures and transformations, tied to the stable part of the North American tectonic plate which would replace NAD83 and serve the broad scientific and geomatics communities by providing a consistent, mm-accuracy, stable reference with which scientific and geomatics results (e.g., positioning in tectonically active areas) can be produced and compared.

Members

Daniel Roman (USA), Chair
Michael Craymer (Canada)
Joe Henton (Canada)
Dru Smith (USA)

Theresa Damiami (USA)
Michael Bevis (USA)
Geoff Blewitt (USA)
Tom Herring (USA)
Jeff Freymueller (USA)
Corné Kreemer (USA)
Richard Snay (USA)

WG 1.3c.3: Reference Frame Transformations in North America

Chair: *Michael Craymer* (Canada)

Programme of Activities

To determine consistent relationships between international, regional and national reference frames in North America, to maintain (update) these relationships as needed and to provide tools for implementing these relationships.

Members

Michael Craymer (Canada), Chair
Daniel Roman (USA)
Dru Smith (USA)

SC 1.3d: Africa (AFREF)

Chair: *Elifuraha Saria* (Tanzania)

Terms of Reference

Sub-commission 1.3d (Africa) is concerned with the definition and realization of a unified continental reference frame (AFREF) for Africa, which will be consistent and homogeneous with the global International Terrestrial Reference Frame (ITRF).

Objectives

In collaboration with the IAG community and its services, regional organisations, and the National and Regional Mapping Organizations of Africa, the objectives of Sub-commission 1.3d (Africa) are:

- Coordinate the activities of the regional organisations focusing on exchange of data, competences and results;
- Promote operation of permanent GNSS stations, in connection with IGS whenever appropriate, as the basis for the long-term maintenance of regional reference frames;
- Promote open access to the GNSS data from permanent GNSS stations used for the maintenance of regional reference frames and scientific applications;
- Develop specifications for the definition and realization of regional reference frames, including the vertical component;
- Encourage and stimulate the development of the AFREF project in close cooperation with IGS and other interested organizations;
- Encourage and assist countries, within each regional organisation, to re-define and modernize their national geodetic systems, compatible with the ITRF;
- Support the efforts of the United Nations Initiative on Global Geospatial Information Management (UN-GGIM) towards a sustainable Global Geodetic Reference Frame (GGRF).

Structure

- Chair: *Elifuraha Saria* (Tanzania)
- Governing Board (see list of members below)

Programme of Activities

- Provide a forum for addressing activities, results and key issues of common interest to the regional organisations;
- Develop analysis strategies and compare methods for the implementation of the regional reference frames and their expression in the ITRF, in full interaction with the IGS;
- Consider developing tectonic deformation models that will enable transformation of locations within a defined reference frame between different epochs.

Members

Elifuraha Saria (Tanzania), Chair
Emanuel Nkurunziza (Kenya)
Joseph Dodo (Nigeria)
Salah Mahmud (Egypt)
Cesare Mbaria (Kenya)
Prosper Ulotu (Tanzania)
Andre Nonguierma (Burkina Faso)
Akingbade O (Nigeria)
Moha El-Ayachi (Morocco)
Elias Lewi (Ethiopia)
Patrick Vorster (South Africa)
Prof. *Kamal Labbassi* (Morocco)
Active honorary members:
Richard Wonnacott (South Africa)
Hussein Farah (Kenya)
Olajide Kufoniyi (Nigeria)

Some additional members are foreseen to be elected at the AFREF meeting in 2020.

SC 1.3e: Asia-Pacific (APREF)

Chair: *Basara Miyahara* (Japan)

Terms of Reference

Sub-commission 1.3e aims to improve regional cooperation that supports the realization and densification of the ITRF. This activity will be carried out in close collaboration with the Geodetic Reference Framework for Sustainable Development Working Group of the United Nations Global Geospatial Information Management for Asia and the Pacific (UN-GGIM-AP). For more details about UN-GGIM-AP WG1 http://www.un-ggim-ap.org/workinggroups/geodetic.

Objectives

- The densification of the ITRF and promotion of its use in the Asia Pacific region;
- To encourage the sharing of GNSS data from Continuously Operating Reference Stations (CORS) in the region;
- To develop a better understanding of crustal motion in the region;
- To promote the collocation of different measurement techniques, such as GNSS, VLBI, SLR, DORIS and tide gauges, and the maintenance of precise local geodetic ties at these sites; and
- To outreach to developing countries through symposia, workshops, training courses, and technology transfer activities.

Program of Activities

The activities of Asia-Pacific Sub-commission will principally be those of the Asia-Pacific Reference Frame (APREF) project. The APREF project consists of a Central Bureau, Network operators, Data centers, and Analysis centers. The Central Bureau, within Geoscience Australia, functions as the 'day-to-day' APREF coordinating body. Specifically, the Central Bureau ensures that APREF products are made available to the global geodetic community. Furthermore, they are the combination center responsible for analyzing, combining and validating the individual solutions of the contributing Analysis Centers, and for expressing the combined solution in the ITRF. Following APREF data and products are provided with an open access data policy via the internet following the practice of the IGS. They consist of daily GNSS RINEX data, station log files, weekly coordinate estimates in SINEX format, and APREF network and time-series plots. For more details, see http://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/asia-pacific-reference-frame.

Members

The members of the Asia-Pacific Sub-commission are national geodetic representatives from the UN-GGIM-AP member nations and APREF participating organisations.

UN-GGIM-AP WG1 (Geodetic Reference Frame)
Basara Miyahara (Japan), Chair
John Dawson (Australia), vice-Chair
Yamin Dang (China)
S. K. Singh (India)
Mohd Yunus (Malaysia)
Dalkhaa Munkhtsetseg (Mongolia)
Graeme Blick (New Zealand)
Sangoh Yi (South Korea)

APREF Analysis Group
Guorong Hu (Australia)
Alex Woods (Australia)
Yunbin Yuan (China)
Basara Miyahara (Japan)

SC 1.3f: Antarctica

Chair: *Martin Horwath* (Germany)

Terms of Reference

Sub-commission 1.3f focuses on the realization and densification of a unified reference frame for Antarctica, which will be consistent with the global International Terrestrial Reference Frame (ITRF). The Sub-commission shares objectives and activities of the Scientific Committee on Antarctic Research (SCAR), namely of the SCAR Expert Group Geodetic Infrastructure of Antarctica (GIANT). The Sub-commission closely links IAG and SCAR activities by embedding identical activities, with identical persons where indicated, into the two complementary organisational structures.

Objectives

- Maintenance and densification of the precise geodetic reference network in Antarctica by permanent observations and GNSS campaigns;
- Realization of a unified vertical datum including GNSS ties of tide gauges;
- Providing unified reference for further GNSS applications like airborne gravimetry, ground truthing for satellite missions, geodynamics and glaciology;
- Develop technologies for remote geodetic observatories;

- Stimulate and coordinate international collaboration on the above fields, under the unique political conditions of Antarctic research given by the Antarctic Treaty, in order to make optimum use of logistics and infrastructure.

Program of Activities

- Organization of GNSS campaigns in Antarctica;
- Extend activities for the operation of remote permanent GNSS stations;
- Maintenance of the data archive (SCAR GNSS data base) to collect Antarctic GNSS data and provide them to the scientific community;
- Data analysis and determination of the Antarctic GNSS network as a regional densification of ITRF;
- Provide homogeneous site velocities for e.g. glacial isostatic adjustment determination;
- Support airborne surveys and satellite missions with precise terrestrial reference;
- Collaborate with IAG Sub-Commission 3.4 (Cryospheric Deformation) and the SCAR Scientific Research Programme Solid Earth Response and Influence on Cryosphere Evolution (SERCE) and subsequent programmes, respectively
- Organize special workshop(s) on the consistent analysis of GNSS data and realization of ITRF
- Organize meetings/sessions at conferences like IAG, IUGG, SCAR Open Science Conference.

Members

Martin Horwath (Germany), Chair
Alessandro Capra (Italy)
Mirko Scheinert (Germany)
Manuel Berrocoso (Spain)
Graeme Blick (New Zealand)
Koishiro Doi (Japan)
Rene Forsberg (Denmark)
Thomas James (Canada)
Aspurah Kamburov (Bulgaria)
Matt King (Australia)
Kenichi Matsuoka (Norway)
Alexey Matveev (Russia)
Gennadi Milinevsky (Ukraine)
Elizabeth Petrie (United Kingdom)
Markku Poutanen (Finland)
Goncalo Prates (Portugal)
Lars Sjoberg (Sweden)
Norbertino Suarez (Uruguay)
Terry Wilson (USA)
Andres Zakrajsek (Argentina)

Working Groups of Sub-Commission 1.3

WG 1.3.1: Time-dependent transformations between reference frames in deforming regions

Chair: *Richard Stanaway* (Australia)

Terms of Reference

This WG will review different approaches used to enable transformation between reference frames within plate boundary zones and regions affected by glacial isostatic adjustment. These transformations are necessarily time-dependent to account for interseismic strain and also episodic seismic deformation. In these instances conformal transformations do not adequately model the complexity of the deformation field and other approaches are required to enable high precision transformations at different epochs of the source and target reference frames.

Deformation models and other time-dependent transformation models provide linkages between global reference frames such as ITRF, regional reference frames and local reference frames commonly used for positioning, land surveying, mapping and GIS.

The WG will collaborate with other regional reference frame working groups to develop a global deformation and transformation model schema. This will require development of a standardized deformation model format that can be accessed from international registries of geodetic parameters such as those hosted by ISO/TC 211 and IOGP/EPSG. WG 1.3.1 will work closely with FIG Commission 5 (Positioning and Measurement), specifically FIG Working Group 5.2 (Reference Frames). WG members comprise of a wide spectrum of researchers from different fields of geophysics, geodesy, land surveying and GIS.

List of members

Richard Stanaway (Australia), Chair
Wan Anom Wan Aris (Malaysia)
Elmar Brockmann (Switzerland)
Miltiadis Chatzinikos (Greece)
Yingyang Cheng (China)
Michael Craymer (Canada)
Chris Crook (New Zealand)
Nic Donnelly (New Zealand)
Kristian Evers (Denmark)
Jeff Freymueller (USA)
Pasi Häkli (Finland)
Muzaffer Kahveci (Turkey)
Kevin Kelly (USA)
Martin Lidberg (Sweden)

Niraj Manandhar (Nepal)
Basara Miyahara (Japan)
José Antonio Tarrío Mosquera (Chile)
Chris Pearson (New Zealand)
Susilo Sarimun (Indonesia)

Corresponding members:
Graeme Blick (New Zealand)
Carine Bruyninx (Belgium)
Xavier Collileux (France)
Paul Denys (New Zealand)
Craig Roberts (Australia)
Yoshiyuki Tanaka (Japan)
Norman Teferle (G.-D. Luxembourg)

SC 1.4: Interaction of Celestial and Terrestrial Reference Frames

Chair: *Zinovy Malkin* (Russia)

Terms of Reference

International terrestrial and celestial reference frames, ITRF and ICRF, respectively, as well as the tie between them expressed by the Earth Orientation parameters (EOP) are key products of geodesy and astrometry. The requirements to all the components of this triad grow steadily and the mm/μas level of accuracy is the current goal of the astronomic and geodetic community.

The current computation procedures for ITRF and ICRF are based on multi-stage processing of observations made with several space geodetic techniques: VLBI, SLR, GNSS, and DORIS. Not all of them provide equal contributions to the final products. The latest ITRF realizations have been derived from combination of normal equations obtained from all four techniques, whereas the ICRF is a result of a single global VLBI solution. The latter is tied to the ITRF using an arbitrary set of reference stations. But VLBI relies on the ITRF origin provided by satellite techniques and shares responsibility with SLR for the ITRF scale. And all the techniques contribute to positions and velocities of ITRF stations.

This situation causes complicated mutual impact of ITRF and ICRF, which should be carefully investigated in order to improve the accuracy of both reference systems and the consistency between each other and EOP. The subject becomes more and more complicated when moving to millimeter accuracy in all components of this fundamental triad. As a consequence, we face systematic errors involving the connection between the ICRF and ITRF realizations, which cannot be fixed by datum correction during the current solution.

Objectives

Several issues are currently preventing the realization of the terrestrial and celestial reference systems (TRF and CRF, respectively) at the mm/μas level of accuracy, such as: (a) insufficient number and non-optimal distribution of active and stable (systematically and physically) stations (VLBI and SLR in the first place) and radio sources, (b) technological (precision) limitations of existing techniques, (c) incompleteness of the theory and models, and (d) not fully understood and agreed-upon details of the processing strategy. These issues are the subject of research of the IAG Sub-Commission 1.4.

Working Groups of Sub-Commission 1.4

WG 1.4.1: Improving and unification of geophysical and astronomical modeling for better consistency of reference frames

Chair: *Daniel MacMillan* (USA)

Terms of Reference

WG 1.4.1 is aimed to promote and coordinate investigations of the impact of geophysical and astronomical modeling on the terrestrial and celestial reference frames (TRF and CRF) and the consistency between CRF, TRF, and Earth orientation parameters (EOP), the latter serving as the transformation parameters between TRF and CRF. The primary attention will be given to VLBI as the only technique nowadays that can provide highly consistent global solutions for TRF, CRF, and EOP.

Objectives

- Encourage and develop cooperation and collaboration in theoretical studies, simulations, and processing of real data aimed at a better understanding of the impact of geophysical and astronomical modeling on TRF, CRF, and EOP derived from VLBI observations.
- Advance means of comparing models as well as TRF, CRF, and EOP realizations.
- Compare different theoretical models and their realizations used by VLBI analysis centers. Study the propagation of differences in those models to differences in geodetic and astrometric products.
- Develop practical recommendations for VLBI analysis centers and the IERS Conventions Center on the optimal models to be used during processing of VLBI observations.

List of members

Robert Heinkelmann (Germany)
Hana Krasna (Austria, Czech Republic)
Sebastien Lambert (France)
Daniel MacMillan (USA), Chair
Zinovy Malkin (Russia)
David Mayer (Austria)
Lucia McCallum (Australia)
Tobias Nilsson (Sweden)
Stanislav Shabala (Australia)

WG 1.4.2: Improving VLBI-based ICRF and comparison with Gaia-CRF

Chair: *Sébastien Lambert* (France)

Terms of Reference

WG 1.4.2 is aimed to review the current CRF status, to identify deficiencies and to make proposals for improvements. The WG will pay a particular attention to the next ICRF VLBI realization, ICRF3 extension or ICRF4, which should be a significant improvement over ICRF3 in respect of number of core and supplement radio sources, uncertainty and accuracy of the source position, and uniform distribution over the sky. Moreover, the Gaia mission is expected to improve an optical realization of the CRF with precision similar to the ICRF and with 1–2 order of magnitude more objects. However, as the set of extragalactic objects suitable for both optical and radio observation is limited, one goal of the WG is to identify such objects, oversee the relevant observations, and to analyze the data to permit the best possible connection between the radio and optical CRF realizations.

Objectives

- Analyze the ICRS/ICRF definition in view of the latest developments in astrometry and space geodesy.
- Study systematic errors in the current individual CRF and ICRF realizations.
- Review systematic differences between CRF realizations at different wavelengths due to, e.g., core-shift or host galaxies.
- Analyze different modeling options and analysis strategies of computation of the next ICRF realization.
- Develop optimal procedures to align GCRF to ICRF.

List of members

Christopher Jacobs (USA)
Maria Karbon (Germany)
Sebastien Lambert (France), Chair
Daniel MacMillan (USA)
Zinovy Malkin (Russia)
Francois Mignard (France)
Jacques Roland (France)
Manuela Seitz (Germany)

JWG 1.4.3: Consistent realization of TRF, CRF, and EOP (joint with IAU Commission A2 and IERS)

Chair: *Robert Heinkelmann* (Germany)
Vice-Chair: *Manuela Seitz* (Germany)

Terms of Reference

Many applications, e.g. in geodesy, astronomy, or navigation, rely on the consistency between terrestrial (TRF) and celestial (CRF) reference frames and Earth Orientation Parameters (EOP). The EOP connect the CRF and TRF in terms of their orientation and rotation differences. The EOP can only be considered as physically meaningful when determined consistently with the reference frames. The quality requirements for the applications including societal contributions were quantified through the IAG GGOS as 1 mm accuracy and 0.1 mm/yr stability, i.e. about 33 µas and 3.3 µas/yr in terms of EOP. For Earth system science based on EOP the consistency is a crucial characteristic. Today, the quality requirements for reference frames and EOP are not met.

Data and model inconsistency. Currently, TRF and CRF are determined independently of each other. Individual Working Groups (CRF) or Combination Centers (TRF) compute the frames through reprocessing/combination efforts every five to ten years. The releases of the terrestrial and celestial frames do not happen at the same time. In this way, the frames are computed based on different input data and on different analysis models in case of updates of the conventional models. Following independent approaches, the consistency of a new release of one of the frames can only be quantified and thus ensured to the last release of the respective other frame. If the frames are not fully consistent, the EOP based on these frames cannot be consistent.

Multi-technique vs. single technique analysis. DORIS, GNSS, SLR and VLBI observations are combined with local tie vectors at co-location sites for the TRF computation, whereas the CRF is directly connected to the TRF through VLBI alone. This situation does not change when applying alternative data analysis procedures. Nevertheless, as VLBI networks are sparse in comparison to multi-technique networks, it has been shown that the terrestrial part of the Earth orientation significantly improves through the combination with satellite-based data. The celestial parts of Earth orientation, dUT1 (UT1 ~ ERA) and CPO, determined by VLBI observations only – and possibly by LLR data –, can in turn improve due to correlations between the EOP within the VLBI data analysis. CRF realizations in other wavelengths are aligned to the X/S VLBI CRF and thus, do not contribute to the CRF orientation for ICRF3. Nevertheless, they allow for an independent validation. Apart from the rotation and spin, catalogues based on Gaia (optical) data releases can provide independent insight into deformations and other technique-dependent systematic errors and thus present another independent validation for the VLBI-based CRF.

Prediction problem. The reference frames and the EOP are customarily applied in prediction mode, e.g. for geodetic and astrometric data analyses. Accordingly, values have to be given beyond the data time span considered for the reference frame realization. As long as no significant non-linearity occurs, the global coordinates can be used very well for predicting the position into the future. For most of the applications, predicted EOP have to be available as well. The predicted EOP require consistency to the frames and to the reprocessed EOP at the same time. It is impossible to fulfill both requirements when new reference frame releases become available.

Objectives

Addressing the abovementioned issues, the working group will:

- compute multi-technique CRF-TRF solutions together with EOP in one step, which will serve as a basis to quantify the consistency of the current conventional reference frames and EOP as well as the consistency of reprocessed and predicted EOP;
- investigate the impact of different analysis options, model choices and combination strategies on the consistency between TRF, CRF, and EOP;
- study the differences between multi-technique and VLBI-only solutions;
- study the differences between VLBI solutions at different radio wavelengths;
- study the differences between Gaia (optical) and VLBI (radio) reference frames;
- study the effects on the results, when different data time spans are considered;
- compare the practically achievable consistency with the quality requirements theoretically addressed by IAG GGOS; and
- derive conclusions about future observing systems or analysis procedures in case the quality requirements cannot be met with the current infrastructure and approaches.

List of members

Claudio Abbondanza (USA)
Sabine Bachmann (Germany)
Liliane Biskupek (Germany)
Christian Bizouard (France)
Xavier Collilieux (France)
Aletha de Witt (South Aftica)
Anastasiia Girdiuk (Germany)
David Gordon (USA)
Robert Heinkelmann (Germany), Chair, IERS Analysis Coordinator
Christopher Jacobs (USA)
Shuanggen Jin (China)
Hana Krasna (Austria)
Sebastien Lambert (France)
Karine Le Bail (USA)
Daniel MacMillan (USA)
Zinovy Malkin (Russia), representative of IAG SC 1.4
David Mayer (Austria)
Manuela Seitz (Germany), Vice-Chair
Benedikt Soja (USA)
Nickolas Stamatakos (USA)

Corresponding members

Alberto Escapa (Spain), representative of IAU Comm. A2
Richard Gross (USA)
Florian Seitz (Germany), representative of IAU Comm. A2
Jean Souchay (France)
Daniela Thaller (Germany), Director of IERS Central Bureau

Proposed cycle

Classical cycles: IAG WG (4 year cycle), IAU WG (3 year cycle), IERS WG (2 year cycle). A 4-year cycle is proposed in order to be compliant with IAG bylaws as the initiative and thus the primary affiliation of this JWG is with IAG.

Commission 2 – Gravity Field

President: **Adrian Jäggi** (Switzerland)
Vice President: **Mirko Reguzzoni** (Italy)

https://com2.iag-aig.org/

Terms of Reference

The accurate determination of the gravity field and its temporal variations is one of the three fundamental pillars of modern geodesy (besides of geometry/kinematics and Earth rotation). This is essential for applications in positioning and navigation, civil and aerospace engineering, metrology, geophysics, geodynamics, oceanography, hydrology, cryospheric sciences and other disciplines related to the Earth's climate and environment. IAG Commission 2 was established at the IUGG in Sapporo in summer 2003 for promoting, supporting, and stimulating the advancement of knowledge, technology, and international cooperation in the geodetic domain associated with the Earth's gravity field.

Since most of the scientific themes are of long-term interest, large parts of the structure of Commission 2 are continued on the same basis as in the previous period 2015-19. Main drivers for the activities of the present period 2019-23 are related to the IAG resolutions adopted at the XXVII IUGG General Assembly 2019 in Montreal, concerning the establishment of the International Height Reference System (IHRS) and the establishment of the Infrastructure for the International Gravity Reference Frame (IGRF).

Commission 2, at the start of the new period, consists of six sub-commissions (SCs), plus some Joint Study Groups (JSG) and Joint Working Groups (JWG), all of them jointly with other Commissions and/or services. The sub-commissions cover the following scientific topics:

- Terrestrial (land, marine, airborne) gravimetry and relative/absolute gravity networks;
- Geoid, Physical Height Systems and Vertical Datum Unification;
- Satellite gravity missions;
- Regional geoid determination;
- Satellite altimetry;
- Gravity inversion and mass transport in the Earth system.

Commission 2 has strong links to other commissions, GGOS, IGFS, ICCT and other components of IAG. Connections to these components are created through joint working groups (JWGs) and joint study groups (JSGs) that provide a cross-disciplinary stimulus for work in several topics of interest to the commission, and the joint organization of meetings.

The main tasks of Commission 2 in the period 2019-23 are among others:

- Establishment of a Global Absolute Gravity Reference System (GAGRS) to replace the International Gravity Standardization Net 1971 (IGSN71), which no longer fulfills the requirements and accuracy of a modern gravity reference; especially to include time-dependent gravity variations;
- Supporting the realization of an International Height Reference System (IHRS);
- Supporting the realization of a Global Geodetic Reference System (GGRS);
- Analysis of current and future satellite data (CHAMP, GRACE, GOCE, GRACE-FO) and the release of improved global gravity field models (satellite only models and in combination with terrestrial data and satellite altimetry);
- Promoting future gravity mission constellations for assuring the continued monitoring of global gravity and mass transport processes in the Earth system;
- Assuring the future of the comparison campaigns of absolute gravimeters;
- Investigating modern relativistic methods and geodetic metrology with special focus on gravity field and height determination;

- Fostering regional gravity and geoid determination and integration of regional models into a global reference;
- Understanding of physics and dynamics of the Earth sub-systems and mass transport processes in the Earth system;
- Providing contributions to operationalization of mass transport modelling and stimulation of new applications;
- Fostering communication with user communities;
- Assisting the IGFS and its components in improving their visibility and their services;
- Assisting the regional sub-commissions in establishing contacts and in acquiring data.

The necessary WGs and SGs can be established at any time and they can be dissolved when they reached their goals or if they are not active.

Objectives

The main objectives of Commission 2 are as listed in the IAG by-laws:

- Terrestrial, marine and airborne gravimetry
- Satellite gravity field observations
- Gravity field modeling
- Time-variable gravity field
- Geoid and height determination
- Satellite orbit modeling and determination
- Satellite altimetry for gravity field modeling

Structure

Sub-Commissions

SC 2.1: Land, Marine and Airborne Gravimetry
Chair: *Derek van Westrum* (USA)

SC 2.2: Geoid, Physical Height Systems and Vertical Datum Unification
Chair: *George Vergos* (Greece)

SC 2.3: Satellite Gravity Missions
Chair: *Frank Flechtner* (Germany)

SC 2.4: Regional Geoid Determination
Chair: *Hussein Abd-Elmotaal* (Egypt)

SC 2.4a: Gravity and Geoid in Europe
Chair: *Heiner Denker* (Germany)

SC 2.4b: Gravity and Geoid in South America
Chair: *Maria Cristina Pacino* (Argentina)

SC 2.4c: Gravity and Geoid in North and Central America
Chair: *Xiaopeng Li* (USA)

SC 2.4d: Gravity and Geoid in Africa
Chair: *Hussein Abd-Elmotaal* (Egypt)

SC 2.4e: Gravity and Geoid in Asia-Pacific
Chair: *Cheinway Hwang* (China-Taipei)

SC 2.4f: Gravity and Geoid in Antarctica
Chair: *Mirko Scheinert* (Germany)

SC 2.5: Satellite Altimetry
Chair: *Xiaoli Deng* (Australia)

SC 2.6: Gravity Inversion and Mass Transport in the Earth System
Chair: *Wei Feng* (China)

Joint Study Groups

JSG 3.1: Geodetic, seismic and geodynamic constraints on GIA (Joint with: Comm 1, Comm 3)
Chair: R. Steffen (Sweden)

JSG T.28: Forward gravity field modelling of known mass distributions (Joint with: ICCT, Comm 3, GGOS)
Chair: *D. Tsoulis* (Greece)

JSG T.35: Advanced numerical methods in physical geodesy (Joint with: ICCT, GGOS)
Chair: *R. Čunderlík* (Slovakia)

JSG T.23: Spherical and spheroidal integral formulas of the potential theory for transforming classical and new gravitational observables (Joint w.: ICCT, GGOS)
Chair: *M. Šprlák* (Australia / Czech Republic)

JSG T.26: Geoid/quasi-geoid modelling for realization of the geopotential height datum (Joint with: ICCT, GGOS)
Chair: *J. Huang* (Canada), *Y.M. Wang* (USA)

JSG T.25: Combining geodetic and geophysical information for probing Earth's inner structure and its dynamics (Joint with: ICCT, Comm 3)
Chair: *R. Tenzer* (China)

JSG T.34: High resolution harmonic analysis and synthesis of potential fields (Joint with: ICCT, GGOS)
Chair: *S. Claessens* (Australia)

JSG T.30: Dynamic modeling of deformation, rotation and gravity field variations (Joint w.: ICCT, Comm 3)
Chair: *Y. Tanaka* (Japan)

JSG X.X: Machine learning in geodesy (Joint with: ICCT, Comm 1, Comm 3, Comm 4, GGOS)
Chair: *B. Soja* (USA)

JSG T.37: Theory and methods related to high-resolution digital topographic and bathymetric models (Joint with: ICCT, Comm 1, Comm 3, GGOS)
Chair: *D. Carrion* (Italy)

Joint Working Groups

JWG 2.1.1: Establishment of the International Gravity Reference Frame (joint with IGFS, BGI, IGETS)
Chair: *Hartmut Wziontek* (Germany)

JWG 2.1.2: Unified file formats and processing software for high-precision gravimetry Frame (joint with IGFS, IGETS, BGI)
Chair: *Ilya Oshchepkov* (Russia)

JWG 2.2.1: Error assessment of the 1 cm geoid experiment (joint with ISG, IGFS)
Chair: *Martin Willberg* (Germany)

JWG C.3: Geodesy for the Cryosphere: advancing the use of geodetic data in polar climate modelling (Joint with: ICCC, Comm 3)
Chair: *Bert Wouters* (Netherlands)

JWG C.4: Sea level and vertical land motion (Joint with: ICCC, Comm 1, Comm 4, GGOS)
Chair: *Roelof Rietbroek* (Germany)

JWG C.5: Understanding the monsoon phenomenon from a geodetic perspective (Joint with: ICCC, Comm 3, Comm 4, GGOS)
Chair: *Balaji Devaraju* (India)

JWG C.6: Numerical Simulations for Recovering Climate-Related Mass Transport Signals (Joint with: ICCC, GGOS)
Chair: *Roland Pail* (Germany)

JWG C.7: Satellite geodetic data assimilation for climate research (Joint with: ICCC, GGOS)
Chair: *Mehdi Khaki* (Australia)

JWG C.8: Methodology of comparing/validating/testing climate simulations to/with geodetic data (Joint with: ICCC, ICCT)
Chair: *Jürgen Kusche* (Germany)

JWG Q.1: Quantum gravimetry in space and on ground (Joint with: IAG Project QuGe)
Chair: *F. Pereira* (France)

JWG Q.2: Laser interferometry for gravity field missions (Joint with: IAG Project QuGe)
Chair: *M. Murböck* (Germany)

JWG Q.3: Relativistic geodesy with clocks (Joint with: IAG Project QuGe)
Chair: *G. Petit* (France)

Program of Activities

The Gravity Field Commission fosters and encourages research in the areas of its sub-entities by facilitating the exchange of information and organizing Symposia, either independently or at major conferences in geodesy. The activities of its sub-entities, as described below, constitute the activities of the Commission, which will be coordinated by the Commission and summarized in annual reports to the IAG Bureau.

The principal symposia that will be organized jointly by Commission 2 and the IGFS in the next period will be held in Austin in September 2020 and in 2022 (location TBD). The other two symposia where a Commission 2 meeting will be held are the IAG Scientific Assembly 2021 in Beijing, China, and the IUGG General Assembly 2023 in Berlin, Germany.

The status of Commission 2, including its structure and membership, as well as links to the internet sites of its sub-entities and parent and sister organizations and services, will be updated regularly and can be viewed on the web site: https://com2.iag-aig.org/.

Steering Committee

President Commission 2: *Adrian Jäggi* (Switzerland)
Vice President Comm. 2: *Mirko Reguzzoni* (Italy)
Chair Sub-Comm. 2.1: *Derek van Westrum* (USA)
Chair Sub-Comm. 2.2: *George Vergos* (Greece)
Chair Sub-Comm. 2.3: *Frank Flechtner* (Germany)
Chair Sub-Comm. 2.4: *Hussein Abd-Elmotaal* (Egypt)
Chair Sub-Comm. 2.5: *Xiaoli Deng* (Australia)
Chair Sub-Comm. 2.6: *Wei Feng* (China)
Representative of IGFS: *Riccardo Barzaghi* (Italy)
Representative of ICCT: *Pavel Novák* (Czech Republic)
Member-at-Large: *Laura Sanchez* (Germany)
Member-at-Large: *Min Zhong* (China)
Immediate Past President: *Roland Pail* (Germany)

The steering committee will meet at least once per year. These meetings are open for all interested IAG members.

Sub-Commissions, Working Groups and Study Groups

SC 2.1: Gravimetry and Gravity Network

Chair: *Derek van Westrum* (USA)
Vice-Chair: *Przemyslaw Dykowski* (Poland)

Terms of Reference

Geodesists and geophysicists utilize gravity and gravity gradient datasets from a wide variety of sources: local relative gravity campaigns, pointwise absolute gravity observations, gravity variation in time at fixed locations, and continental scale observations from marine and airborne platforms. These observations need to be consistent with each other, consistent with satellite-based results, and have well defined accuracy/uncertainty determinations. IAG Sub-commission 2.1, "Land, Marine and Airborne Gravimetry" aims to bring together scientists from all over the globe that are interested in the instruments, techniques, and analysis of terrestrial, marine and airborne gravity and gravity gradient measurements.

Objectives

SC2.1 provides the scientific community with the means to assess the accuracy of absolute gravity observations through the organization of regular international absolute gravimeter comparisons. These efforts are in cooperation with the metrology community: the Consultative Committee on Mass and Related Quantities, its Working Group on Gravimetry (CCM WGG), and other Regional Metrology Organizations as well as all interested scientific institutions. The relationship allows for direct traceability of gravity data to international standards.

SC2.1 supports the dissemination of the results of these activities through an international absolute gravity database, which in turn, will support the ongoing realization of a new and improved International Gravity Reference Frame.

SC2.1 supports sharing expertise and experience in performing gravity surveys on moving platforms (Marine, Airborne) allowing for the collection of the highest possible quality gravity data using the most up to date techniques.

To facilitate the exchange of all terrestrial gravity data and metadata, SC2.1 is actively supporting the creation of a unified file format in an open source environment.

Finally, SC2.1 promotes research and development into new instruments and techniques by stimulating communication and cooperation between scientific groups. The subcommission will encourage regional meetings and workshops dedicated to specific problems when and where appropriate.

Program of Activities

- Host the JWG2.1.1, "Establishment of an International Gravity Reference Frame", along with IGFS, BGI and IGETS
- Host the JWG 2.1.2 "Unified file formats and processing software for high-precision gravimetry," along with IGFS, BGI and IGETS
- Host the SG2.1.1 "Developments in near Earth gravimetry: instruments, analysis, and applications"
- Provide access to the results of comparisons of absolute gravimeters via the AGrav database at BKG-BGI
- Appoint the Steering Committee consisted of the members experienced in the fields of gravimetry related to the activities of SC2.1 and the contact persons for European, East Asia and Western Pacific, South America and North America Gravity Networks.

Support IAG Commission 2 Symposia such as GGHS.

SG 2.1.1: Developments in Gravity Instrumentation, Analysis, and Applications

Chair: *Derek van Westrum* (USA)
Vice-Chair: *Przemyslaw Dykowski* (Poland)

Terms of Reference

SG2.1.1 is focused on methods and instrumentation used in collecting and analyzing terrestrial (non-satellite) gravity and gravity gradiometry data. New developments in both "classic" and quantum absolute instruments, as well as novel relative instruments, are happening a rapid pace and are of great interest to the geodetic community. In addition, communication of such developments between the geodesy community and metrology community is essential.

SG2.1.1 also supports research in the analysis of gravity data. Examples include standard absolute corrections, barometric loading, reduction of relative gravity networks, software, and file formats.

SG2.1.1 also promotes innovations in the use of gravity and gravity gradient data. As examples, time varying gravity signals are being used to fine tune ice melt models, biological processes, and of course, geoid change.

Objectives

- Communication between research groups developing novel instruments and the community of gravity scientists
- Coordination of scientific efforts regarding mobile platforms.
- Promotion and coordination in the establishment and measurements of regional gravity networks.
- Organization of scientific workshops and meetings for the discussion of techniques and methods of terrestrial gravity measurements.

Members

Chair: *Derek van Westrum* (USA)
Vice Chair: *Przemyslaw Dykowski* (Poland)
Mirjam Bilker-Koivula (Finland)
Sylvain Bonvalot (France)
John Crowley (Canada)
Yoichi Fukuda (Japan)
Silvia Alicia Miranda (Argentina)
Ilya Oshchepkov (Russia)
Wu Shuqing (China)
Hartmut Wziontek (Germany)

JWG 2.1.1: Establishment of the International Gravity Reference Frame

(joint with IGFS, BGI, IGETS)

Chair: *Hartmut Wziontek* (Germany)
Vice-Chair: *Sylvain Bonvalot* (France)

Terms of Reference

One task of IAG's Commission 2 "Gravity Field" is the establishment of the International Gravity Reference System and Frame (IGRF). These activities are motivated by the IAG Resolutions No. 2 of 2015 (IUGG General Assembly Prague) and No. 4 of 2019 (IUGG General Assembly Montreal). The IAG Sub-Commission 2.1 "Land, Marine and Airborne Gravimetry" promotes consistency and compatibility of gravity and gravity gradient datasets and assessment of their accuracy. The International Gravity Field Service IGFS coordinates the servicing of the geodetic and geophysical community with gravity field related data, software and information. A modern and precise absolute gravity reference frame will not only contribute to the establishment of the Global Geodetic Reference Frame (GGRF) of the UN, but will also serve as a long-term and precise gravity reference for the IAG Global Geodetic Observing System (GGOS).

Objectives

Within IAG Sub-Commission 2.1 "Land, Marine and Airborne Gravimetry" the realization of the International Gravity Reference Frame (IGRF) will be initiated. The IGRF is the implementation of the International Gravity Reference System (IGRS). The IGRS is defined by the observation of the instantaneous acceleration of free fall, the traceability of these observations to the International System of Units (SI), and a set of conventional corrections for the time independent components of gravity effects. The IGRF as the realization of the IGRS is based on observations with absolute gravimeters (AG) which are monitored at reference stations and during comparisons. The IGRF further defines a set of conventional models for the correction of temporal gravity changes. Finally, the IGRF demands a compatible infrastructure accessible to end-users.

The JWG focuses on the establishment of such an infrastructure in cooperation with IGFS, GGOS, international and national institutions, agencies, and governmental bodies. This infrastructure should consist of reference stations on the national level for the monitoring of AGs. On the international level, comparison stations will provide the facilities to check the consistency of AGs within their reported uncertainty estimates, and core stations will link to space geodetic techniques and the International Height Reference Frame (IHRF).

The absolute gravity database "AGrav" which already is a fixed part of the BGI (International Gravimetric Bureau) services is proposed to serve as a central inventory to document all IGRF stations and related AG observations.

A close cooperation with the International Geodynamics and Earth Tide Service (IGETS) supports the continuous monitoring at the gravity reference stations. The collaboration with the Working Group on Gravimetry of the Consultative Committee on Mass and Related Quantities (CCM-WGG) ensures good practice in the field of AG comparisons.

The activities should be further aligned with the JWG on the Implementation of the International Height Reference Frame.

Members

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Przemyslaw Dykowski (Poland)
Andreas Engfeldt (Sweden)
Reinhard Falk (Germany)
Jaakko Mäkinen (Finland)
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Janis Kaminskis (Latvia)
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Jakub Kostelecky (Czech Republic)
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Axel Rülke (Germany)
Laura Sanchez (Germany)
Roman Sermyagin (Russia)
Heping Sun (China)
V.M. Tiwari (India)

JWG 2.1.2: Unified file formats and processing software for high-precision gravimetry frame

(joint with IGFS, IGETS, BGI)

Chair: *Ilya Oshchepkov* (Russia)
Vice-Chair: *Vojtech Pálinkáš* (Czech Republic)

Terms of Reference

Absolute gravity measurements have become widely used in geodesy since the 1970s when several transportable absolute gravimeters were introduced, since then their number has increased dramatically and continues to do so. The absolute gravimeters are used not only in geodesy, but also in metrology, geophysics, hydrology and other applications. The IAG's Commission 2 "Gravity Field" and its JWG 2.1.1 are working on the establishment of the International Gravity Reference System/Frame (IGRS/IGRF), which will be based solely on the absolute gravity measurements. The latter task will require a possibility for re-processing of all historical, current and future data, as well as their long-term availability for all interested parties.

The current ability to exchange and to re-process raw data of absolute gravity measurements is limited by the fact that each manufacturer uses their own proprietary software and different data storage formats. Also differences in the implementation of processing standards may exist. In such a situation it is difficult to ensure reproducibility and traceability to the SI of an individual experiment. Another difficulty arises from the requirement for a re-processing of old measurements after the introduction of new processing standards, when neither data nor software are available anymore.

The JWG 2.1.2 aims to create a unified, meter and software independent, format for storing and sharing not only the processing results and metadata, but also the raw data of gravity measurements. Different software will be evaluated and discrepancies will be discovered and resolved. Perspectively, an open source software should be established to eliminate the above mentioned problems, as well as to implement a standard procedure for handling absolute gravity measurements for the IGRF. The activities need a close cooperation with the manufacturers of absolute gravimeters in order to align instrument specific data handling and a transparent processing and to implement a common exchange format.

Objectives

- Review of existing software, data types, data formats and processing standards in high-precision gravimetry; develop requirements for a unified format and data processing software.
- Test of the compatibility of existing software

- Develop a unified data storage format for high-precision gravity measurements: description, converter and software implementation.
- Develop a unified processing software to process any high-precision gravity measurements with a wide support for any processing procedure.

Members

Brian Ellis (USA)
Jacques Liard (Canada)
Jeffrey Kennedy (USA)
Jaakko Mäkinen (Finland)
Sergey Svitlov (Germany)
Pierre Vermeulen (France)
Marc Véronneau (Canada)
Hartmut Wziontek (Germany)
Sylvain Bonvalot (France)
Vadim Nagormyi (USA)
Igor Sizikov (Russia)
Christian Ullrich (Austria)
Axel Rülke (Germany)
Domenico Iacovone (Italy)
Alessandro Germak (Italy)
Shuqing Wu (China)
Derek Van Vestrum (USA)
Mirjam Bilker-Koivula (Finland)
Przemyslaw Dykowski (Poland)

SC 2.2: Geoid, Physical Height Systems and Vertical Datum Unification

Chair: *George Vergos* (Greece)
Vice-Chair: *Rossen S. Grebenitcharsky* (Saudi Arabia)

Terms of Reference

A global height reference frame with high accuracy and stability is required to determine the global changes of the Earth. A major step towards this goal was taken by the IAG resolution (No. 1) for the definition and realization of an International Height Reference System (IHRS), adopted at the IUGG 2015 meeting in Prague and the IAG resolution (No. 3) for the establishment of the International Height Reference Frame (IHRF), adopted at the IUGG 2019 meeting in Montreal.

Given the work carried out for the general methodological scheme for geoid and potential determination, the data prerequisites and practical studies, it has become apparent that the IHRS should be globally realized with common standards in terms of the processing strategy. Moreover, the use of all available data sources, e.g., GNSS-derived heights, satellite altimetry, topography/bathymetry, local gravity (terrestrial, airborne and marine) as well as the latest global geopotential models, should be employed in order to properly model the high-frequency part of the gravity field spectrum. Such combination of heterogenous data has been deemed a mandatory in order to reduce the omission error as well as to properly model the contribution of topography.

Traditional levelling might also be integrated on a regional or local scale. Finally, the unification of local/national vertical reference frames to regional ones and their link to the IHRF is of main importance, employing local geoid realizations and datum definitions.

The IAG SC 2.2 aims at bringing together scientists and geodesists concerned with methodological questions in geoid and potential determination, who in different ways contribute to reach the above-mentioned goal of a global height system realization and unification. It includes topics (state of art methodologies for processing, analyzing, utilizing data, unifying datums, etc.), and ranging from regional gravimetric geoid determination to the realization and implementation of IHRS in view of the existing regional/local/national height system realizations and 3D vertical datum (geoid) definitions.

Objectives

The IAG Sub-Commission 2.2 (SC2.2) promotes and supports scientific research related to methodological questions in geopotential, geoid and height determination, both from the theoretical and practical perspectives. The former refers in particular on methodological questions and practical numerical applications contributing to the realization of IHRS with the required sub-centimeter accuracy, the combination of local/regional vertical reference frames and their unification to the IHRF. This includes for instance:

- Realization of the International Height Reference System (support to the Joint Working Group with the GGOS Focus Area Unified Height System "Implementation of the International Height Reference Frame (IHRF)")
- Height system unification at regional scales and unification to the IHRF.
- Studies on W_0 determination.
- Studies on data requirements, data quality, distribution and sampling rate to reduce the omission error to the sub-centimeter level in different parts of the world.
- Contributions of alternate data sources, such as altimetry sea surface heights and GNSS geometric heights to geopotential modeling and geoid determination at reference benchmarks.
- Investigation of the theoretical framework required to compute the sub-centimeter geoid (support of ICCT SG:

Geoid/quasi-geoid modelling for realization of the geopotential height datum)
- Investigation of the error budget od potential determination and vertical reference frames unification (support to Commission 2 WG: Error assessment of the 1 cm geoid experiment)
- Investigation and benchmarking of alternative regional geoid determination methods and software.
- Studies on theoretical and numerical problems related to the solution of the geodetic boundary value problems (GBVPs) in geoid determination,
- Studies on time variations of the gravity field and heights due to Glacial Isostatic Adjustment (GIA) and land subsidence.
- Development of relativistic methods for potential difference determination using precise atomic clocks (support of Working Group X.3).
- Investigating the role of traditional levelling in future regional/local height system realizations combined with all available data linked to Earth's geopotential determination.
- Investigating the utilizations of already defined national and regional geoid models together with new types of Geodetic Earth Observations (GEOs) and based on theoretical and practical developments linked to mixed GBVPs.

Program of Activities

- Organizing meetings and conferences.
- Organization of local/regional workshops for the promotion of IHRF related studies.
- Inviting the establishment of Special Study Groups on relevant topics.
- Reporting activities of SC2.2 to the Commission 2.
- Communication/interfacing between different groups/ fields relevant to the realization of IHRS.
- Conceptual and methodological support to working groups for national & regional vertical datums and reference frames definitions as realizations of IRHS.

JWG 2.2.1: Error assessment of the 1 cm geoid experiment

(joint with ISG, IGFS)

Chair: *Martin Willberg* (Germany)
Vice-Chair: *Tao Jiang* (China)

Terms of Reference

The realization of the International Height Reference System (IHRS) will be based on reference stations, which are calculated from a local combination of global gravity field models and regional gravity observations. This process, which is called regional geoid/gravity modeling is realized with different philosophies and theories inside the geodetic community. However, the final quality of the IHRS depends heavily on the consistency of all included modeling methods. Consequently, in the previous IAG period, within JWG 2.2.2 an effort was made to evaluate the differences in various regional geoid/gravity modeling approaches and standardize them to a specific degree.

Within 'the 1 cm geoid experiment' 15 participating groups have calculated a regional geoid/gravity model in the area of Colorado, US. Thereby, all groups used identical input data sets consisting of terrestrial and airborne gravity observations. After two iterations within 'the 1 cm geoid experiment', differences of a few centimeters remain between the final results of the contributing groups. Manifold reasons might be responsible for this difference, but major aspects are assumed to be differences in the procedure, the topographic reduction, and the individual data handling. Until now, the quality assessment of individual solutions was mainly analyzed by their variation from a joint mean value, which was interpreted as reference. However, the Colorado area contains a Geoid Slope Validation Survey (GSVS), where positions, gravity values and deflections of the vertical were measured with very high quality along a set of 223 benchmarks. These values and the results of the GSVS processing are not yet published, but will be open to the public soon, thereby providing an improved reference (for this JWG).

The objectives of this JWG are to validate the results, to identify and quantify potential error sources, and to develop and improve methods for deriving realistic error estimates of the gravity potential values at the IHRS stations. Once available, the differences of individual geoid/height anomaly results to the improved reference from the GSVS shall be analyzed. The most possible reasons for these differences should be worked out. Especially, a modified computation set-up shall be defined, which enables to separate method-related and data-driven error contributions. This will be important to quantify the error level caused by different regional gravity modelling methods. If possible, these errors shall be further reduced within an additional iteration step. Furthermore, different methods should be examined for their ability to estimate an appropriate error budget for the final results. This is of great importance, as the assessment of the total error is needed for the reference stations in the IHRS. Lessons from this JWG should then be transferred to the JWG for 'Implementation of the International Height Reference Frame – IHRF'.

Program of Activities

- Analyze the difference of various solutions to the GSVS reference
- Quantify the main error contributors of regional geoid modeling
- Estimation of the total error budget
- Derive recommendations for the IHRS realization from the viewpoint of regional gravity field modeling
- Organize conference sessions
- Report activities

Members

Chair: *Martin Willberg* (Germany)
Vice-Chair: *Tao Jiang* (China)
Laura Sánchez (Germany)
Yan Ming Wang (USA)
Vassilios Grigoriadis (Greece)
Marc Véronneau (Canada)
Sten Claessens (Australia)
Qing Liu (Germany)
Rene Forsberg (Denmark)
Hussein Abd-Emotaal (Egypt)
Koji Matsuo (Japan)
Bihter Erol (Turkey)
Jonas Ågren (Sweden)
Kevin Ahlgren (USA)
Matej Varga (Czech/Croatia)
Riccardo Barzaghi (Italy)
Representative person USP (Brazil)

SC 2.3: Satellite Gravity Missions

Chair: Frank Flechtner (Germany)
Vice-Chair: Matthias Weigelt (Germany)

Terms of Reference

The successful launches of the German CHAMP (2000), the US/German GRACE (2002), the ESA GOCE (2009) and US/German GRACE-FO (2018) missions have led to a revolution in global gravity field mapping by space-borne observation techniques. These missions are the only measurement systems which can directly observe mass distribution and mass transport in the Earth system based on proven new concepts and technologies, such as high-low satellite-to-satellite tracking (SST) using the GPS constellation, low-low SST based on micro-wave and laser ranging, and satellite gravity gradiometry (SGG), as well as space-borne accelerometry.

GRACE has produced 15+ years consistent long- to medium-wavelength global gravity field models and its temporal changes till June 2017 which are extended since May 2018 by GRACE-FO data. GOCE provided high- accuracy and high-resolution static gravity field models. In combination with complementary gravity field information from terrestrial data and satellite altimetry, an even higher spatial resolution can be achieved. Consequently, these satellite missions provide valuable contributions to many geoscientific application fields, such as geodesy, hydrology, oceanography, glaciology, and solid Earth physics.

Objectives

The focus of SC 2.3 will be to promote and stimulate the following activities:

- providing the scientific environment for the development of the next generation of static and temporal gravity field solutions based on observations from the satellite gravity missions CHAMP, GRACE, GOCE, and GRACE-FO, as well as optimum combination with complementary data types (SLR, terrestrial and air-borne data, satellite altimetry, etc.),
- developing alternative methods and new approaches for global gravity field processing with special emphasis on functional and stochastic models and optimum data combination,
- fostering the exchange of knowledge and data among processing entities,
- communication and interfacing with gravity field model user communities (climatology, oceanography/altimetry glaciology, solid Earth physics, geodesy, ...) as well as relevant IAG organizations such as the GGOS

Committee on Satellite and Space Missions and the GGOS Bureau of Products and Standards,

- identification, investigation and definition of enabling technologies for future gravity field missions such as observation types, technologies or mission architectures, and
- triggering new gravity field mission proposals and supporting their implementation.

Program of Activities

The sub-commission will establish, if necessary, Working Groups on relevant topics. The Steering Committee will work closely with members and other IAG commissions and sub-commissions to obtain mutual goals. Also it will promote and jointly sponsor special sessions at IAG Symposia and other workshop/conferences.

SC 2.4: Regional Geoid Determination

Chair: *Hussein Abd-Elmotaal* (Egypt)
Vice-Chair: *Xiaopeng Li* (USA)

Terms of Reference and Objectives

Sub-commission 2.4 is concerned with the following areas of investigation:

- Regional gravity and geoid sub-commissions: data sets, involved institutions, comparison of methods and results, data exchange, comparison with global models, connection of regional models
- Gravimetric geoid modelling techniques and methods, available software, new alternative geoid determination techniques
- GNSS/levelling geoid determination: methods, comparisons, treating and interpretation of residuals, common treatment of gravity and GNSS/levelling for geoid determination
- Geoid applications: GNSS heights, sea surface topography, integration of geoid models in GNSS receivers, vertical datums.
- Other topics: topographic effects, downward and upward continuation of terrestrial, airborne, satellite data specifically as applied to geoid modelling.

Program of Activities

Sub-Commission 2.4 is going to initiate and coordinate regional gravity and geoid sub-commissions. It will encourage and support the data exchange between agencies and will assist local, regional and national authorities in their projects of gravity field determination. It will help in organizing courses and symposia for gravity field determination.

Steering Committee

Chair SC2.4: *Hussein Abd-Elmotaal* (Egypt)
Chair SC2.4a: *Heiner Denker* (Germany)
Chair SC2.4b: *Maria Cristina Pacino* (Argentina)
Chair SC2.4c: *Xiaopeng Li* (U.S.)
Chair SC2.4d: *Hussein Abd-Elmotaal* (Egypt)
Chair SC2.4e: *Cheinway Hwang* (China-Taipei)
Chair SC2.4f: *Mirko Scheinert* (Germany)

SC 2.4a: Gravity and Geoid in Europe

Chair: *Heiner Denker* (Germany)

Terms of Reference

The primary objective of the sub-commission is the development of improved regional geoid and quasigeoid models for Europe, which can be used for applications in geodesy, oceanography, geophysics and engineering, e.g., height determination with GNSS techniques, vertical datum definition and unification, dynamic ocean topography estimation, geophysical modelling, and navigation. Another emerging field is related to the development of new optical clocks in physics with relative uncertainties at the level of 10^{-18}, as in accordance with the laws of general relativity, such clocks are sensitive to the gravity potential at the level of 0.1 m^2/s^2, equivalent to 1 cm in height.

The geoid and quasigeoid modelling will be based mainly on terrestrial gravity and terrain data in combination with state-of-the-art global geopotential models. In this context, upgraded terrestrial data sets as well as the utilization of GRACE and GOCE based global geopotential models led to significant improvements. The evaluation of the latest European gravimetric quasigeoid models by GNSS and levelling data indicates an accuracy potential of 1 – 2 cm on a national basis, and 2 – 4 cm at continental scales, provided that high quality and resolution input data are available within the area of interest. Further improvements can be expected from the inclusion of upgraded gravity field data sets, especially in areas with hitherto insufficient input data.

Program of Activities

- Utilization of state-of-the-art global geopotential models.
- Identification and acquisition of new terrestrial data sets, including gravity, terrain, and GPS/levelling data.
- Merging and validation of all data sets.
- Investigation of refined mathematical modelling techniques and numerical tests.
- Computation of new geoid and quasigeoid models.
- Evaluation of the results by GNSS/levelling data.

- Study of applications, such as vertical datum definition and unification, dynamic ocean topography estimation, ground truth for optical clocks, etc.

Delegates

The regional sub-commission for Europe SC2.4a cooperates with national representatives from most of the countries in Europe and reports to sub-commission 2.4. The existing contacts and successful cooperation with the respective persons and national and international agencies shall be continued and extended.

SC 2.4b: Gravity and Geoid in South America

Chair: *Maria Cristina Pacino* (Argentina)
Vice-Chair: *Gabriel do Nascimento Guimarães* (Brazil)

Terms of Reference and Objectives

The Sub Commission 2.4b entitled Gravity and Geoid in South America, as part of the Commission 2 of IAG, was established as an attempt to coordinate efforts to establish a new Absolute Gravity Network in South America, to carry out gravity densification surveys, to derive a geoid model for the continent as a height reference and to support local organizations in the computation of detailed geoid models in different countries.

Besides, a strong effort is being carried out in several countries in order to improve the distribution of gravity information, to organize the gravity measurements in the continent and to validate the available gravity measurements.

The main objectives of the project are:

- To re-measure existent absolute gravity stations and to encourage the establishment of new stations.
- To validate fundamental gravity network from different countries in order to establish a single and common gravity network for South America.
- To adjust national gravity networks and to link them together.
- To obtain and to maintain files with data necessary for the geoid computation like gravity anomalies, digital terrain models, geopotential models and satellite observations (GPS) on the levelling network of different countries.
- To provide a link between the different countries and the IGFS in order to assure access to proper software and geopotential models for local geoid computation.
- To compute a global geoid model for South and Central America using the available data. To encourage countries to cooperate by releasing data for this purpose.
- To encourage and eventually support local organizations in different countries endeavoring to increase the gravity data coverage, to improve the existing digital terrain models, to carry out GPS observations on the levelling network and to compute a high resolution geoid.
- To organize and/or encourage the organization of workshops, symposia or seminars on gravity and geoid determination in South America.
- To test and to use future geopotential models derived from the modern missions (GRACE and GOCE) as well as any new combined model.
- To support the IAG Sub-Commission 1.3b (Reference Frame for South and Central America, SIRGAS) in the activities related to the unification of the existing vertical datums.
- Establish close connections with SC2.4c (Gravity and Geoid in North and Central America) to have a good overlap of data coverage in Central America and the Caribbean.

Delegates

Chair: *Maria Cristina Pacino* (Argentina)
Co-Chair: *Gabriel do Nascimento Guimarães* (Brazil)
Henry Montecino Castro (Chile)
Oscar Carranco (Ecuador)
Ana Crisitina Oliveira Concoro de Matos (Brasil)
Ayelén Pereira (Argentina)
Roberto Teixeira Luz (Brasil)
Silvia Alicia Miranda (Argentina)
Ivonne Gatica Placencia (Chile)
Norbertino Suárez (Uruguay)
Jorge Faure Valbi (Uruguay)

SC 2.4c: Gravity and Geoid in North and Central America

Chair: *Xiaopeng Li* (USA)
Vice-Chair: *David Avalos* (Mexico)

Terms of Reference and Objectives

The primary objective of this Sub-commission is the development of a regional gravity field and geoid model covering the region of North America and Central America by 2022 in order to achieve a common vertical datum. The region involved will encompass Iceland, Greenland, Canada, the U.S.A. (including Alaska and Hawaii), Mexico, countries forming Central America, the Caribbean Sea and the northern parts of South America. This model will serve as the official realization of the vertical datum for countries that want to adopt it.

The intention is to ensure that a suitable North American Geoid is developed to serve as a common datum for everyone in the region. All countries in the region would be served by having access to a common model for translating oceanographic effects to terrestrial datums for various scientific, commercial, engineering and disaster prepared-ness applications. Likewise, it shall serve as the basis for the forthcoming International Great Lakes Datum in 2022 (IGLD 2020).

The achievement of a geoid model for North and Central America will be accomplished by coordinating activities among agencies and universities with interest in geoid theory, gravity, gravity collection, gravity field change, geophysical modelling, digital elevation models (DEM), digital density models (DDM), altimetry, dynamic ocean topography, levelling and vertical datums. Of particular interest will be relating geoid and ocean topography models to ocean topography and tidal benchmarks, taking advantage of the recent satellite altimetry and geopotential field products.

The determination of a geoid model for North and Central America is not limited to a single agency, which will collect all necessary data from all countries. The Sub-commission encourages theoretical diversity in the determination of a geoid model among the agencies. Each agency takes responsibility or works in collaboration with neighboring countries in the development of a geoid model for their respective country with an overlap (as large as possible) over adjacent countries. Each solution will be compared, the discrepancies will be analyzed, and the conclusions will be used to improve on the next model.

Program of Activities

The Sub-commission will support geoid activities in countries where geoid expertise is limited by encouraging more advanced members to contribute their own expertise and software. The Sub-commission will encourage training and education initiative of its delegates (e.g., ISG geoid school, graduate studies and IPGH technical cooperation projects). Starting on 2011 the Sub-commission will organize regular meetings with representatives of Central American and Caribbean countries to promote an increase of expertise as well as to create a wide network of specialists.

The chair (or a delegate representative) of the Sub-commission will meet with the equivalent European and South American projects to discuss overlap regions and to work towards agreements to exchange data. The delegates of the Sub-commission will keep close contact with all related Study Groups of the IAG. The Sub-commission is open to all geodetic agencies and universities across North and Central America with an interest in the development of a geoid model for the region. The meetings of the Sub-commission 2.4c are open to everyone with interests in geodesy, geophysics, oceanography and other related topics.

The delegates will communicate primarily using e-mail. In addition, starting on November 9, 2015, Canada (CGS), USA (NGS) and Mexico (INEGI) will organize audio/video conferences every four weeks to discuss activity plans and present results. The sub-commission also plans to organize annual meetings if enough delegates can be present. Preferably, these meetings will be held during international conferences;. Minutes of meetings will be prepared and sent to all delegates of the Sub-commission.

Delegates

Chair: *Xiaopeng Li* (USA)
Vice-Chair: *David Avalos* (Mexico)
Rene Forsberg (Denmark)
Jianliang Huang (Canada)
Dan Roman (USA)
Laramie Potts (USA)
Yan Min Wang (USA)
Vinicio Robles (Guatemala)
Carlos E. Figueroa (El Salvador)
Anthony Watts (Cayman Islands)
Oscar Meza (Honduras)
Alvaro Alvarez (Costa Rica)
Wilmer Medrano (Nicaragua)
Christopher Ballesteros (Panama)

SC 2.4d: Gravity and Geoid in Africa

Chair: *Hussein Abd-Elmotaal* (Egypt)
Vice-Chair: *S.A. Benahmed Daho* (Algeria)

Terms of Reference

The African Gravity and Geoid sub-commission (AGG) belongs to the Commission 2 of the International Association of Geodesy (IAG). The main goal of the African Gravity and Geoid sub-commission is to determine the most complete and precise geoid model for Africa that can be obtained from the available data sets. Secondary goals are to foster cooperation between African geodesists and to provide high-level training in geoid computation to African geodesists.

Objectives and Activities

The objectives and activities of the sub-commission are summarized as follows:

- Identifying and acquiring data sets - gravity anomalies, DTMs, GPS/levelling, seismic Moho.
- Training of African geodesists in geoid computation.

- Merging and validating gravity data sets.
- Computing African geoid models.
- Evaluating the computed geoid models using GPS/levelling data.
- Updating the geoid models using new data/strategies to obtain better geoid accuracy (dynamic process).

Delegates

Chair: *Hussein Abd-Elmotaal* (Egypt)
Vice-Chair: *S.A. Benahmed Daho* (Algeria)
Addisu Hunegnaw (Ethiopia)
Ahmed Abdalla (Sudan)
Atef Makhloof (Egypt)
Ayman Hassan (Egypt)
Bernhard Heck (Germany)
Charles Merry (South Africa)
Hassan Fashir (Sudan)
Ismail Ateya Lukandu (Kenya)
John B.K. Kiema (Kenya)
Joseph Awange (Kenya)
Joseph Kamguia (Cameroun)
Karim Owolabi (Namibia)
Kurt Seitz (Germany)
Mostafa Abd-Elbaky (Egypt)
Mostafa Ashry (Egypt)
Norbert Kühtreiber (Austria)
Patroba Odera (Kenya)
Peter Nsombo (Zambia)
Prosper Ulotu (Tanzania)
Walyeldeen Godah (Sudan)

SC 2.4e: Gravity and Geoid in the Asia-Pacific

Chair: *Cheinway Hwang* (China-Taipei)
Vice-Chair: *Wenbin Shen* (China)

Context

There are about 48 counties in the Asia-Pacific (AP) region. Many countries in the region have invested considerable resources on improved geoid models. Recent progress in satellite altimetry greatly increases coastal marine gravity accuracy. Satellite remote sensing data have been used to generate digital elevation models that are needed for geoid modeling. Many countries now increase their GNSS/leveling observation campaigns to collect data to assess and to control the qualities of gravimetric quasi/geoid models. All such datasets allow to improve geoid models in the Asia Pacific region.

Terms of Reference and Objectives

This sub-commission is a continuation of the previous sub-commission and will continue to promote gravity data collection, geoid processing and evaluating techniques, and geoid applications in the Asia-Pacific region. In particular, coastal marine gravity will be improved by recent altimetry data. We will organize workshops to exchange data and techniques of geoid modeling and assessing.

Program of Activities

a) Gravity and Related Data

- share available gravity data
- share available DEMs along common borders
- combine resources for terrestrial gravity surveys along common borders
- promote regional airborne gravity surveys
- determine improved coastal gravity anomalies from satellite altimetry

b) Gravimetric geoid and hybrid geoid quality control

- share GNSS/levelling and vertical deflection data for geoid quality control
- promote regional GNSS/leveling and vertical deflection campaigns
- connect regional vertical datums

c) Education & Research

- organize meetings and workshops to improve modeling and evaluation techniques of gravimetric quasi/geoids, and to promote their application to height modernization and vertical datum connection.
- propose technical sessions in scientific and professional conferences
- propose matters of common concern/interest

Delegates

Chair: Cheinway Hwang (China-Taipei)
Vice-Chair: *Wenbin Shen* (China)
Jay Hyoun Kwon (Korea)
Will Featherstone (Australia)
Koji Matsuo (Japan)
Ami Hassan Md Din (Malaysia)
Chalermchon Satirapod (Thailand)
Kosashi Prijatna (Indonesia)
Dinh Toan Vu (Vietnam)
Ronaldo Gatchalian (Philippines)
Ropesh Goyal (India)
Matt Amos (New Zealand, corresponding member only)

SC 2.4f: Gravity and Geoid in Antarctica

Chair: *Mirko Scheinert* (Germany)
Vice-Chair: *Fausto Ferraccioli* (UK)

Terms of Reference

Antarctica is the region that still features the largest data gaps in terrestrial gravity. Global gravity field solutions suffer from the lack of terrestrial data in Antarctica as well as from the polar data gap originating from the orbit inclination of dedicated satellite gravity field missions (esp. GOCE with a polar data gap of 1,400 km diameter).

The coverage with terrestrial (ground-based and airborne) gravity data in Antarctica has been improved during the last years. Efforts were successfully accomplished to publish a first Antarctic-wide gravity anomaly grid (Scheinert et al. 2016) and to record data over the polar data gap (Forsberg et al. 2017). However, the gravity data coverage in Antarctica is still insufficient. The data are heterogeneous and exhibit inconsistencies. Due to the vast extension of the Antarctic continent, its hostile environment and the difficult logistic conditions it is a long-lasting task to close the Antarctic data gaps in terrestrial gravity.

SC 2.4f shall pursue this objective and shall facilitate the necessary coordination to release an updated grid of terrestrial gravity data for Antarctica. Terrestrial gravity data are needed for the global high-resolution determination of the Earth's gravity field and/or for a validation of global gravity field models, for a regional improvement of the Antarctic geoid and for geophysical inversion to improve our knowledge on the subglacial topography and inner structure of the Earth.

Thus, SC 2.4f plays an important role to improve the cooperation between all interested scientists of geodesy and of neighbouring disciplines, mainly geophysics.

Program of Activities

- Promoting the collection of surface and airborne gravity data in Antarctica;
- Promoting new gravity surveys in Antarctica, especially airborne gravimetry;
- Promoting the establishment and (re-)measurement of reference gravity stations utilizing absolute gravity meters;
- Promoting the scientific exchange of latest developments in technology (esp. airborne gravimetry) and data analysis;
- Evaluation of existing and new surface and airborne gravity data, validation of global gravity field models in Antarctica;
- Investigation of optimum strategy for the combination of gravity data of different sources;
- Release of updated gridded gravity anomaly dataset(s) for Antarctica to the scientific public;
- Organization of special workshop on airborne geodesy and geophysics (especially aerogravimetry) with focus on Antarctica;
- Focus group for all scientists interested in Antarctic gravity and geoid, and cooperation with similar data initiatives, especially within the Scientific Committee on Antarctic Research (SCAR);

Delegates

Chair: *Mirko Scheinert* (Germany)
Don Blankenship (USA)
Alessandro Capra (Italy)
Fausto Ferraccioli (UK)
Christoph Förste (Germany)
René Forsberg (Denmark)
Larry Hothem (USA)
Graeme Eagles (Germany)
German L. Leitchenkov (Russia)
Jaakko Mäkinen (Finland)
Yves Rogister (France)
Koichiro Doi (Japan)
Michael Studinger (USA)

Corresponding Members
Matt Amos (New Zealand)

SG 2.4.1: Downward Continuation of Airborne Gravity Data for Local Geoid Improvement

Chair: *Xiaopeng Li* (USA)
Vice-Chair: *Jianliang Huang* (Canada)

Terms of Reference

Many countries have used or will use pure gravimetric geoid/quasi-geoid models as their height datum. This requires high accurate and high resolution local gravity data coverage. Airborne gravimetry is widely used for this purpose because of its efficiency both in terms of time and cost. One important step of using airborne gravity data in local geoid modeling is to downward continue the airborne gravity data from flight altitudes to the (quasi)geoid computation level.

The topic of downward continuation (DWC) has been studied for many decades without very conclusive answers on how different methods compare with each other. Often a time, geoid modelers just pick one approach and use it without thorough comparisons. On the other hand, there are vast amounts of airborne gravity data collected by the GRAV-D project at NGS NOAA of the United States and by many other groups around the world. These airborne gravity data are collected on flight lines where the height of the aircraft actually varies significantly, and this causes challenges for users of the data. A downward continued gravity grid either on the topography or on the geoid is still needed for many applications such as improving the resolution of a local geoid model. Several classical and new downward continuation methods, such as, Least Squares Collocation and Residual Least Squares Collocation (RLSC), the Inverse Poisson Integral, Truncated Spherical Harmonic Analysis, and Radial Basis Functions (RBF), are tested on both simulated data sets and real GRAV-D airborne gravity data. Comprehensive theoretical and numerical comparisons are required to provide useful guidelines for correctly handling airborne gravity in local geoid computation.

Objectives

The main objectives of this SG are to:

- Review the theories of the downward continuation of airborne gravity data.
- Provide an official forum for in-depth discussion of very approaches.
- Develop efficient software to perform all considered approaches.
- Conduct in-depth analysis of the downward continuation results.
- Identify main problems and give recommendations.
- Publish downward continued airborne gravity grid and tool boxes.

Program of Activities

- Circulating and sharing information, ideas, progress reports, papers and presentations.
- To launch a proposal for state-of-the-art cooperation on the topic of downward continuation.
- Development/improvement of downward continuation tools.
- Presenting research findings at major international geodetic or geophysical conferences, meetings, and workshops.
- Focus on error assessment of results produced by various methods.
- To open a web page to published downward continued airborne gravity grid products and related software tool boxes.

Members

Chair: *Xiapeng Li* (USA)
Vice Chair: *Jianliang Huang* (Canada)
René Forsberg (Denmark)
Cheinway Hwang (Taiwan)
Roland Klees (Netherlands)
Cornelis Slobbe (Netherlands)
Martin Willberg (Germany)

SC 2.5: Satellite Altimetry

Chair: *Xiaoli Deng* (Australia)
Vice-Chair: *C.K. Shum* (USA)

Terms of Reference

Satellite altimetry missions (e.g., Geosat, TOPEX/Poseidon, ERS-1/2, Envisat and Jason-1/2/3) have been providing vital measurements of global ocean surface topography since 1991. The latest altimetry missions (e.g., HY2a/2b, Ka-band altimetry SARAL/Altika, SAR and SARIn altimetry CryoSat-2 and Sentinel-3A/B, and laser altimetry ICEsat-2) are providing higher resolution observations. The upcoming Jason-CS/Sentinel-6 mission includes two identical satellites scheduled to launch in 2020 (satellite A) and 2025 (satellite B), which will continue measuring the sea level for at least a decade. The future Surface Water and Ocean Topography (SWOT) satellite mission equipped with radar interferometry, due to launch in 2021, will substantially improve measurements of sea surface heights and surface water hydrology at finer scales that has not been possible before. In addition, the in situ GNSS reflectometry (GNSS-R) and the NASA CYGNSS 8-satellite constellation have been providing water/sea level, land cover, water/snow extents, wave and wind measurements.

Altimetry observations cover the global oceans, cryosphere, sea-ice, ice-covered oceans and inland water bodies, providing invaluable geodetic and climatic information for studying the Earth and ocean dynamics (e.g., sea level, ocean wave and wind speed, ocean surface topography, tides, soil moisture, snow depth, ice sheet, ice caps, mountain glacier, inland water and solid Earth deformation), and geophysical features (e.g., marine gravity field, mean sea surface and bathymetry).

The growing altimetry datasets are driving technological leaps forward for satellite geodesy and oceanography. At the same time, they will bridge an observational gap on a spatial-temporal domain critical for solving interdisciplinary problems of considerable societal benefit. The purpose of this IAG sub-commission is to promote innovative research using historic and future altimeter observations to study local, regional, and global geophysical processes, with emphasis on emerging cross-disciplinary applications using satellite altimetry, and in combination with other in situ data sets and techniques including hydrography data, GNSS-R, CYGNSS, SAR/InSAR and GRACE/GOCE.

Objectives

Sub-Commission 2.5 will:

- Establish a close link between this sub-commission and the International Altimeter Service (IAS) and data product providers, in order to (1) establish scientific forums to discuss new results, (2) bring new algorithms from expert research into data production, and (3) encourage development of data products that more directly facilitate cross-disciplinary applications using satellite altimetry;
- Promote innovative applications of satellite altimetry, including evaluations and cross-disciplinary applications of future satellite altimetry;
- Continue developing techniques to improve altimeter data quality, aiming towards the development of new data products across the coastal zones including the coastal ocean, estuaries and inland water bodies;
- Focus on capabilities of the very high spatial resolution from SAR and SARAL altimeters, as well as upcoming SWOT, for precisely modelling the marine gravity field, mean sea surface, bathymetry and ocean mean dynamic topography, as well as temporal variations induced by solid Earth processes and the global terrestrial water cycle; and
- Promote cross-disciplinary research on the shapes and temporal variations of land/ice/ocean surfaces, such as studies of long-term ocean variability, regional and global sea level changes, mountain glaciers/ice-sheet ablations/accumulations, permafrost degradation, coastal and ice-shelf ocean tides, vertical displacements at major tectonic-active zone, land subsidence and other geophysical processes.

Program of Activities

This sub-commission will

- Organize independent workshops or special sessions in major meetings to promote altimetric applications in interdisciplinary earth sciences, and to increase the visibility of IAG in altimetric science; and
- Provide independent forums for potentially improved altimetry data processing and data product access, to encourage innovative and interdisciplinary scientific research and applications of satellite altimetry.

SC 2.6: Gravity Inversion and Mass Transport in the Earth System

Chair: *Wei Feng* (China)
Vice-Chair: *Roelof Rietbroek* (Germany)

Terms of Reference

Spatial and temporal variations of gravity are related to the dynamics of the Earth's interior, land surface, oceans, cryosphere, and atmosphere. The geoid maps equilibrium dynamic processes in the ocean and in the Earth's mantle and crust, and large-scale coherent changes in gravity result from mass transports in atmosphere, hydrosphere, cryosphere, and the ocean, and across these. The gravity field, derived from terrestrial and space gravimetry (SLR, CHAMP, GRACE, GOCE, GRACE-FO, NGGM, …) with unprecedented accuracy and resolution, provides a unique opportunity to investigate gravity- solid earth coupling, the structure of the globe from the inner core to the crust, and mass transports such as those associated within the global water cycle. Gravimetry also contributes to a better understanding of the interactions in the Earth system, and to its response to climate change and the anthropogenic fingerprint.

Objectives

- To further the understanding of the physics and dynamics of the Earth's interior, land surface, cryosphere, oceans and atmosphere using gravity and other geodetic and geophysical measurement techniques.
- To promote the study of solid Earth mass (re-)distribution from gravity and gravity gradient tensor variations, e.g. crust thickness, isostatic Moho undulation, mass loadings, basin formation, thermal effects on density, deformations, as well as interactions with the Earth's interior.
- To advance the investigation of mass transports in the Earth system, and, in particular, to contribute to the understanding of the global water cycle, of the storage of water in cryosphere and hydrosphere, of the fluxes across these sub-systems and the atmosphere, and of sea level.
- To contribute to the operationalization of mass transport monitoring, e.g. for water resource monitoring.
- To aid in reconciling multiple geodetic observations at various spatio-temporal scales for mass transport monitoring and interpretation.

- To stimulate new techniques and potential applications of gravimetry and mass transport monitoring, e.g. quantum gravimeter, optical clock, new satellite gravimetry concept,
- To communicate with gravity-related communities in oceanography, hydrology, cryosphere, solid Earth, geodesy, etc.

Program of Activities

The sub-commission will establish Work Groups (WGs) on relevant topics. The Steering Committee will work closely with members and other IAG commissions and sub-commissions to obtain mutual goals. Also it will promote and jointly sponsor special sessions at IAG Symposia and other workshop/conferences.

WG 2.6.1: Geodetic observations and physical interpretations in the Tibetan Plateau

Chair: *Wenbin Shen* (China)
Vice-Chair: *Cheinway Hwang* (China-Taipei)

Terms of Reference

Mass transport and (re-)distribution of the Tibetan Plateau is a research hotspot in the field of geoscience, relevant to global climate, glaciers, lakes, permafrost and deep geodynamics. The mountain building processes and their dynamic mechanisms of the Tibetan Plateau are still unclear and remain a key topic of research in geosciences. As multiple-type of data continue rapidly to grow on the Tibetan Plateau, advanced techniques in signal processing are needed to effectively extract targeted signals. Cross-correlations between different data types are important keys to discover the connections between the data, and to understand the causes and the consequences of the phenomena of interest.

This working group will concentrate on but not limit to the studies of hydrological change, crustal deformation, regional gravity field and its variation, mass migration and Moho variation, geodynamic and cryospheric processes and climate change of the Tibetan Plateau, based on various observations from space-borne and terrestrial sensors, such as GNSS, GRACE, GRACE-FO, satellite altimetry, InSAR, and ground gravity. Relevant investigations and studies will significantly promote the understanding and revealing of the uplift processes and dynamic mechanisms of mass transport in the Tibetan Plateau.

Objectives

- Hydrological change over river basins, lake level variation, permafrost, vertical deformation, mountain glacier change, atmospheric circulation of the Tibetan Plateau, and their interpretations from altimeter, GNSS, GRACE, GRACE-FO, and gravimeters;
- Geopotential and orthometric height determinations and unification of world height datum systems;
- Long-term monitoring of surface processes from satellite altimeters such as ICESat, TOPEX, Jason-1, -2, and -3, ERS-1, -2, ENVISAT, and Sentinel series;
- Results of satellite and terrestrial-based gravimetric observations;
- Results of GNSS observations, GNSS meteorology, and ionosphere;
- Geophysical interpretations and consequences of gravity, GNSS, satellite altimetry, and seismic observations;
- SAR and LiDAR detections of surface deformation, especially over the Tibetan Plateau;
- Crust structure and density refinement especially in the Tibetan region using multi-datasets;

Members

Chair: *Wenbin Shen* (China)
Vice-Chair: *Cheinway Hwang* (China-Taipei)
Carla Braitenberg (Italy)
Benjamin Fong Chao (China-Taipei)
Tonie van Dam (Luxembourg)
Xiaoli Deng (Australia)
Hao Ding (China)
Xiaoli Ding (Hong Kong, China)
Jeffrey T. Freymueller (USA)
Yuanjin Pan (China)
Jim Ray (USA)
Mirko Reguzzoni (Italy)
Lorenzo Rossi (Italy)
Xiaodong Song (USA)
CK Shum (USA)
Heping Sun (China)
Wenke Sun (China)
Robert Tenzer (Hong Kong, China)
Leonid Zotov (Russia)

Commission 3 – Earth Rotation and Geodynamics

President: **Janusz Bogusz** (Poland)
Vice President: **Cheng-Li Huang** (China)

https://com3.iag-aig.org/

Terms of Reference

The Earth must be considered as a dynamic system through the study of the global gravity field and its temporal variations, and the global and local deformation at the surface in order to define the Earth's internal structure and dynamics. Consequently, geodynamics is the science that studies how the Earth moves and deforms in response to forces acting on the Earth, whether they derive from outside or inside of our planet. This includes the entire range of phenomena associated with Earth rotation and Earth orientation in space such as polar motion, Universal Time (UT) or Length Of Day (LOD), precession and nutation, the observation and understanding of which are critical to the transformation between terrestrial and celestial reference frames. On the other hand, space and terrestrial geodetic techniques provide key observations to investigate a broad range of geophysical processes, thanks to their high accuracy, precision, and reliable georeferencing.

The modern geodesy successfully supports research and data analysis devoted to variations in Earth rotation, gravitational field and geocenter, caused by mass redistribution within and mass exchange among the Earth's fluid sub-systems, i.e., the atmosphere, ocean, continental hydrosphere, cryosphere, mantle, and core along with geophysical processes associated with ocean tides and the hydrological cycle. It also includes tidal processes such as solid Earth and ocean loading tides, and crust and mantle deformation associated with tectonic motions and isostatic adjustment etc.

Geodesy is an important tool for exploring the geometry and temporal evolution of magma plumbing systems, as well as for monitoring and hazards assessment during volcanic unrest and eruption. Angular momenta and the related torques, gravitational field coefficients, and geocenter shifts for all geophysical fluids are the relevant quantities. They are observed using global-scale measurements and are studied theoretically as well as by applying state-of-the-art models; some of these models are already constrained by such geodetic measurements.

During the last few decades many geophysicists have come to use geodynamics in a more restricted sense to address processes such as plate tectonics and Post Glacial Rebound (PGR) that are dominantly endogenic in nature. Because the Earth as a mechanical system responds to both endogenic and exogenic forces, and because these responses are sometimes coupled, Commission 3 studies the entire range of physical processes associated with the motion and the deformation of the solid Earth.

Present-day ice mass changes induce an immediate elastic deformation of the Earth, while the integrated history of mass changes induces an additional viscoelastic deformation. Traditionally, these have been considered separately, which is a good approximation for long-ago load changes and regions of high mantle viscosity. The present-day and recent past load changes must be modeled together as the rapid viscoelastic relaxation is substantial and not easily separated from the immediate elastic changes.

Reference frames of GIA models are likely computed in the center of mass of the solid Earth frame, while the International Terrestrial Reference Frame (ITRF) is defined with origin at the center of mass of Earth system (including all fluids). This means a frame origin transformation is required to allow direct comparison to measurements in ITRF and ambiguity currently exists over the exact transformation between the two.

Among their many applications, geodetic measurements can now contribute to the study of the different phases of the seismic cycle, as they allow recording static and dynamic displacements during large earthquakes, as well as the slow postseismic and interseismic deformation contributing significantly to the process of monitoring natural hazards and risks. The purpose of Commission 3 is to promote, disseminate, and, where appropriate, to help coordinate research in this broad arena.

Sub-Commission 3.1 (Earth Tides and Geodynamics) addresses direct and indirect tidal phenomena that affect the position of fiducial sites and have to be corrected to provide accurate spatial referencing. Such referencing is needed for the observation and monitoring of changes of the Earth's surface at global, regional and local scales. Therefore, there is a considerable contribution of tidal research to global geodynamics and climate change by providing important constraints to geophysical models.

Sub-Commission 3.2 (Volcano Geodesy) addresses explosion in the quality and quantity of volcano geodetic data, which has created a need for new approaches to data analysis, interpretation, and modeling required for data fusion and joint interpretation, both between geodetic datasets and with other types of volcano monitoring results.

Sub-Commission 3.3 (Earth Rotation and Geophysical Fluids) addresses the space-time variation of atmospheric pressure, seafloor pressure and the surface loads associated with the hydrological cycle, and Earth's (mainly elastic) responses to these mass redistributions.

Sub-Commission 3.4 (Cryospheric Deformation) addresses past and present changes in the mass balance of the Earth's glaciers and ice complexes which both induce present-day deformation of the solid Earth on a range of spatial scales, from the very local to global.

Sub-Commission 3.5 (Seismogeodesy) addresses studying the plate boundary deformation zones and integration of geodetic and seismological monitoring of seismically active areas by increasing and/or developing infrastructures dedicated to broadband observations from the seismic wave band to the permanent displacement.

Commission 3 interacts with Global Geodetic Observing System (GGOS), other Commissions and Services of the IAG as well as with other organizations such as the International Astronomical Union (IAU), International Association of Seismology and Physics of the Earth's Interior (IASPEI), International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) and International Association of Cryospheric Sciences (IACS).

Objectives

- To promote cooperation and collaboration on the theory, modelling and observation of Earth rotation and geodynamics.
- To ensure development of research in Earth rotation and geodynamics by organizing meetings, symposia, and sessions at conferences and general assemblies, by creating working groups on specific topics, and by encouraging the exchange of ideas and data and the comparison of methods and results with the goal of improving accuracy, content, methods, theories, and understanding of Earth rotation and geodynamics.
- To serve the geophysical community by facilitating interactions with organizations that provide the data needed to study Earth rotation and geodynamics.

Structure

Sub-Commissions

SC 3.1: Earth Tides and Geodynamics
Chair: *Carla Braitenberg* (Italy)
SC 3.2: Volcano Geodesy (joint with IAVCEI)
Chair: *Emily Montgomery-Brown* (USA)
SC 3.3: Earth Rotation and Geophysical Fluids
Chair: *Jianli Chen* (USA)
SC 3.4: Cryospheric Deformation
Chair: *Jeff Freymueller* (USA)
SC 3.5: Seismogeodesy
Chair: *Jean-Mathieu Nocquet* (France).

Joint Study Group

JSG 3.1: Geodetic, Seismic and Geodynamic Constraints on Glacial Isostatic Adjustment (joint with IASPEI and IAG Commissions 1 and 2)
Chair: *Rebekka Steffen* (Sweden)

Joint Working Groups

JWG 3.1: Improving Theories and Models of the Earth's Rotation (joint with IAU)
Chair: *José Ferrándiz* (Spain)
JWG 3.2: Global combined GNSS velocity field (joint with IAG Commissions 1 and 2)
Chair: *Alvaro Santamaría-Gómez* (France)

Program of Activities

Commission 3 fosters and encourages research in the areas of its sub-entities by facilitating the exchange of information and organizing symposia, either independently or at major conferences in geodesy or geophysics. Some events will be focused narrowly on the interests of the Sub-Commissions and other entities listed above, and others will have a broader commission-wide focus.

Steering Committee

President Commission 3: *Janusz Bogusz* (Poland)
Vice President Comm. 3: *Chengli Huang* (China)
Chair Sub-Comm. 3.1: *Carla Braitenberg* (Italy)
Chair Sub-Comm. 3.2: *Emily Montgomery-Brown* (USA)
Chair Sub-Comm. 3.3: *Jianli Chen* (USA)
Chair Sub-Comm. 3.4: *Jeff Freymueller* (USA)
Chair Sub-Comm. 3.5: *Jean-Mathieu Nocquet* (France)

Representative of IERS: *Robert Heinkelmann* (Germany)
Representative of IGFS: *Nico Sneeuw* (Germany)
Representative of IGETS: *Hartmut Wziontek* (Germany)
Member-at-Large: *Matt King* (Australia)
Member-at-Large: *Laura Fernández* (Argentina)

Sub-Commissions

SC 3.1: Earth Tides and Geodynamics

Chair: *Carla Braitenberg* (Italy)
Vice-Chair: *Séverine Rosat* (France)

Terms of Reference

SC 3.1 addresses the entire range of Earth tidal phenomena and dynamics of the Earth, both on the theoretical as well as on the observational level. The Earth tide affects many types of high precision instrumentation, be it measurements of position, deformation, potential field or acceleration. The tidal phenomena influence both terrestrial and satellite-borne acquisitions. The tidal potential is a driving force that can be accurately calculated, and the tidal response observable as deformation and variations in Earth orientation and rotation parameters gives information on Earth's rheology.

Instruments sensitive enough to detect the tidal signal, record a large range of periodic and aperiodic phenomena as ocean and atmospheric tidal loading, ocean, atmospheric and hydrospheric non-tidal effects, deformation related to the earthquake cycle and even to gravitational waves, as well as plate tectonics and intraplate deformation.

The periods range from seismic normal modes over to the Earth tides and the Chandler Wobble and beyond, ending at the nutation period. Thus, the time scales range from seconds to years and for the spatial scales from local to continental dimensions. As tidal friction is affecting Earth rotation, all the physical properties of the Earth contribute to the explanation of this phenomenon. Therefore, the research on tidal deformation due to changes of the tidal potential as well as ocean and atmospheric loading are a prerequisite to constrain Earth's rheological properties.

Further, direct and indirect tidal phenomena affect the position of fiducial sites and have to be corrected to provide accurate spatial referencing. Such referencing is needed for the observation and monitoring of changes of the Earth's surface at global, regional and local scales. Therefore, there is a considerable contribution of tidal research to global geodynamics and climate change by providing important constraints to geophysical models.

Modern instrumental developments for which tidal phenomena are relevant are gravimeters and gradiometers based on superconductivity (SG), atom interferometry, microelectromechanical-system (MEMS) gravimeters, Inertial Measurement Units, gravitational wave antennas, satellite gravimetry and atomic clocks. The improvements in gravimetric instrumentation leads to the use of gravimetry as a tool to detect underground mass changes, as naturally occurring hydrologic draughts or fluids injected into the underground for the purpose of temporary storage or for other purposes.

The Earth must be studied as a dynamic system through the study of the global gravity field and its temporal variations, and the global and local deformation at the surface in order to define the Earth's internal structure and dynamics. In the next few years, instrumental developments in portable absolute gravimeters can be expected, and further innovations can be envisaged from the ring laser technology.

The SC 3.1 will follow the instrumental developments and infer innovative applications. These geophysical observations together with other geodetic observations and geological information provide the means to better understand the structure, dynamics and evolution of the Earth system.

The existence of a network of superconducting gravimeters allows continuous monitoring of the gravity signal at selected stations with a precision of better than 10^{-10}. The range of applications of SGs has become very wide and applicable not only to Earth tides investigations, but also to support studies on Earth's seismic cycle and hydrological mass estimates. The SG network has had scientifically close relation to the SC 3.1 and IGETS (International Geodynamics and Earth Tide Service), which distributes the data. Therefore, the Chair of SC 3.1 is responsible for the close cooperation with the IGETS to provide effective service-with science coupling.

Objectives

Objectives of SC 3.1 include:

- to study and implement new observational techniques and improve existing ones, including clinometric and extensometric techniques;
- to demonstrate the importance of long term geodetic stations;
- to predict the signals observable with space geodetic techniques based on high precision terrestrial long term time series;
- to advance tidal data analyses and prediction methods;
- to enhance the models on the interaction among solid Earth, ocean, and atmospheric tides;
- to research the effects of the atmosphere and hydrology on gravity and other geodetic observations;
- to study the response of the Earth at tidal and non-tidal forcing frequencies;
- to study the interplay between tides and Earth rotation;

- to study tides on the planets;
- to study the effects of ocean loading and global water distribution;
- to establish and coordinate working groups on specific topics of interest and relevancy to the understanding of our planet;
- to develop, coordinate and promote international conferences, programs and workshops on data acquisition, analysis and interpretation related to the research fields mentioned above;
- to contribute to the definition and realization of the International Terrestrial Reference Frame via advanced geodynamic models at global, regional and local scales;
- to promote the systematic calibration and intercomparison of absolute and relative gravimeters (superconducting, MEMS as well as traditional spring instruments) ;
- to promote interdisciplinary research in Earth and planetary tides;
- to support the IAG Global Geodetic Observing System (GGOS) in the field of:
  - the integral effect on Earth rotation of all angular momentum exchanges inside the Earth, between land, ice, hydrosphere and atmosphere, and between the Earth, Sun, Moon, and planets,
  - the geometric shape of the Earth's surface (solid Earth, ice and oceans), globally or regionally, and its temporal variations, whether they are horizontal or vertical, secular, periodical or sudden,
  - the Earth's gravity field-stationary and time variable mass balance, fluxes and circulation.

Program of Activities

- Organization of International Symposium on Geodynamics and Earth Tide (GET Symposium held every four years) as well as other thematic conferences together with other Commission 3 SCs if possible.
- Awarding of the outstanding scientists with the Paul Melchior Medal, formerly known as the Earth Tides Commission Medal.
- Organization of special sessions at international meetings.
- Organization of the comprehensive SC meeting together with the IGETS.
- Publishing the outcome of the researches, either as stand-alone publications or as proceedings or special issues of scientific journals.
- Cooperating with other Joint Study Groups (JSG), Joint Working Groups (JWG) or Inter-Commission Projects (ICP) and Committees (ICC).
- Cooperate with GGOS, as mentioned above.

SC 3.2: Volcano Geodesy (joint with IAVCEI)

Chair: *Emily Montgomery-Brown* (USA)
Vice-Chair: *Alessandro Bonforte* (Italy)

Terms of Reference

Geodesy is an important tool for exploring the geometry and temporal evolution of magma plumbing systems, as well as for monitoring and hazards assessment during volcanic unrest and eruption. Geodetic techniques include measurements of both deformation (to determine the magnitude, location, and geometry of subsurface sources of pressure change) and gravity (to assess subsurface mass variations).

Recent decades have seen an explosion in the quality and quantity of volcano geodetic data, which has created a need for new approaches to data analysis, interpretation, and modeling. In addition, geodetic data can have different temporal and spatial resolutions, as well as different origins (ground-, air-, and space-based), and they are best utilized in conjunction with other non-geodetic datasets, like seismicity and gas emissions. New tools are therefore needed for data fusion and joint interpretation, both between geodetic datasets and with other types of volcano monitoring results. This is especially relevant now given the expansion in GEO's Geohazard Supersites and Natural Laboratories initiative to volcanic sites around the globe.

We feel that an IAVCEI (International Association on Volcanology and Chemistry of the Earth's Interior) Commission on Volcano Geodesy is needed to organize the diverse community and promote a better understanding of magmatic processes through geodesy.

Objectives

Objectives of SC 3.2 include:

- foster communication within the volcano geodesy community, particularly between senior and early-career researchers, between scientists from different countries, and between volcano observatories;
- facilitate a coordinated geodetic response to volcanic unrest and eruptions around the world, including the acquisition of, and access to, satellite data;
- ensure high-level geodetic capability at the world's volcanoes through the sharing of best practices; development, testing, and distribution of open-source analysis and modeling tools; standardization of techniques for the measurement and interpretation of geodetic changes; exploitation of new technologies; and capacity-building activities;

- support the establishment and maintenance of databases for volcano geodetic observations, as well as the interoperability between these and other sources of geological, geochemical, and geophysical data related to volcanoes;
- promote volcano geodesy as a tool with broad implications and diverse applications in research, monitoring, and crisis response by serving as a bridge between geodesy and other branches of volcanology; connecting geodesists within the academic community, volcano observatories, space agencies, industry, government institutions, and other organizations; and advocating for the commitment of appropriate resources;
- encourage and enable collaborations between geodesy and other disciplines, given that interdisciplinary approaches to volcano research and hazards assessment offer the best prospects for improving overall understanding of volcanic processes and their impacts;
- implementation and dissemination of new standard approaches, protocols and best practices;
- promotion of common initiatives and projects with other IAG and IAVCEI entities.

Program of Activities

- Organize a scientific conference to define big scientific questions that could be addressed with Volcano Geodesy.
- Organize a scientific workshop with the goals of training early career volcano geodesists, sharing current research, and comparing codes on a standardized synthetic data set.
- Set up and use of social networks for advertising the activities and news and encourage people to use it widely.

SC 3.3: Earth Rotation and Geophysical Fluids

Chair: *Jianli Chen* (USA)
Vice-Chair: *Michael Schindelegger* (Germany)

Terms of Reference

Mass transport in the atmosphere-hydrosphere-mantle-core system, or the “global geophysical fluids”, causes observable geodynamic effects on broad time scales. Although relatively small, these global geodynamic effects have been measured by space geodetic techniques to increasing, unprecedented accuracy, opening up important new avenues of research that will lead to a better understanding of global mass transport processes and of the Earth’s dynamic response. Angular momenta and the related torques, gravitational field coefficients, and geocenter shifts for all geophysical fluids are the relevant quantities. They are observed using global-scale measurements and are studied theoretically as well as by applying state-of-the-art models; some of these models are already constrained by such geodetic measurements.

Objectives

The objective of the SC3.3 is to serve the scientific community by supporting research and data analysis devoted to variations in Earth rotation, gravitational field and geocenter, caused by mass redistribution within and mass exchange among the Earth’s fluid sub-systems, i.e., the atmosphere, ocean, continental hydrosphere, cryosphere, mantle, and core along with geophysical processes associated with ocean tides and the hydrological cycle. The SC complements and promotes the objectives of GGOS with its central theme "Global deformation and mass exchange processes in the Earth system" and the following areas of activities:

- quantification of angular momentum exchange and mass transfer;
- deformation due to mass transfer between solid Earth, atmosphere, and hydrosphere including ice.

Program of Activities

- To promote the exchange of ideas and results as well as of analysis and modeling strategies, sessions at international conferences and topical workshops will be organized.
- In addition, SC 3.3 interacts with the sister organizations and services, particularly with the IERS Global Geophysical Fluids Centre and its operational component with four Special Bureaus (atmosphere, hydrology, ocean, combination) and its nonoperational component for core, mantle, and tides.
- SC 3.3 will have close contacts to the GGOS activities, in particular to the activities of the newly established GGOS Committee “Contributions to Earth System Modelling”.

SC 3.4: Cryospheric Deformation (joint with IACS)

IAG co-Chair: *Jeff Freymueller* (USA)
IACS co-chair: *Bert Wouters* (Netherlands)
Vice-Chair: *Natalya Gomez* (Canada)

Terms of Reference

Past and present changes in the mass balance of the Earth's glaciers and ice complexes induce present-day deformation of the solid Earth on a range of spatial scales, from the very local to global. Geodetic observations that validate, or may be assimilated into, models of glacial isostatic adjustment (GIA) and/or constrain models of changes in present-day ice masses through measurements of elastic rebound are of paramount importance, as are "paleo-geodetic" observations like the history of relative sea level.

Present-day ice mass changes induce an immediate elastic deformation of the Earth, while the integrated history of mass changes induces an additional viscoelastic deformation. Traditionally, these have been considered separately, which is a good approximation for long-ago load changes and regions of high mantle viscosity. In regions of low mantle viscosity (e.g. West Antarctica and Iceland), the present-day and recent past load changes must be modeled together as the rapid viscoelastic relaxation is substantial and not easily separated from the immediate elastic changes. In all cases, present-day geometric measurements (e.g., uplift rates) measure the sum of elastic and viscoelastic deformations, and these components cannot be separated without additional models or observations.

Present-day gravity changes have a different sensitivity to the elastic and viscoelastic components. In addition, it is now clear that 1-D Earth models are no longer sufficient for many problems, but 3-D models pose computational challenges, and careful inter-comparison of 3-D models is required to better understand model differences.

Reference frames of GIA models are likely computed in the center of mass of the solid Earth frame, while the International Terrestrial Reference Frame (ITRF) is defined with origin at the center of mass of Earth system (including all fluids). This means a frame origin transformation is required to allow direct comparison to measurements in ITRF and ambiguity currently exists over the exact transformation between the two.

This SC has a long history as part of IAG. At the Montreal IUGG, it was decided to make this a joint sub-commission with IACS. Within IAG, SC3.4 historically has focused on resolving technical measurement issues. With the new cross-Association sub-commission, we will have a better opportunity to enhance collaboration and dissemination of these measurements within the glaciological community.

Objectives

Objectives of SC 3.4 include:

- improvement of ice loading/unloading histories;
- improvement of Earth rheological models;
- assessment of elastic loading and viscoelastic GIA models using present day geodetic data of all types, or paleo-sea level data;
- assessing the impact of cryospheric deformation on geodetic reference frames and estimates of plate motions, and the differences between the frames of GIA models and the ITRF;
- assessing impact of lateral variations in Earth rheology on interpretations of geodetic and geological data.

Program of activities

- Organize a workshop focused on observation and modeling of cryospheric changes and GIA. There is an opportunity to organize what would likely be a 2-day workshop in conjunction with an upcoming WCRP Grand Challenge workshop, planned for November 2020 in Victoria BC, Canada. In terms of workshops, we will seek partners to enhance cross-disciplinary aspects of the workshops, and have begun discussions with the WRCP/CLIVAR program, the PALSEA program, and JSG 3.1: Geodetic, Seismic and Geodynamic Constraints on Glacial Isostatic Adjustment (*Rebekka Steffen*, Chair). We have approached IRIS about using their Earth Model Collaboration effort for the dissemination and inter-comparison of 3-D viscosity models, and they are eager to include these important Earth models.
- Organize a second workshop in 2022, possibly jointly with the PALSEA community on a topic such as GIA and past and present changes in sea level, geomorphology and landscape evolution. We have begun discussions with PALSEA on this, although their future activities will depend on a funding renewal.
- Organize a working group to analyze frame differences (especially frame origin) between GIA models and ITRF. It should be possible to transform global GIA model predictions into any reference frame, including Center of mass of Earth System and Center of Figure. We should encourage future modeling efforts to compute the needed frame transformations.
- Develop an online archive of 1D and 3D Earth rheological models to enhance dissemination and inter-comparison of these models. The IRIS Earth Models Collaboration (http://ds.iris.edu/ds/products/emc/) offers a promising suite of tools and archive capability, and they are eager to work with us. The IRIS EMC includes open-source software tools for dealing with their model format, and we will try to encourage development of tools to compare and use these viscosity models, and to transform seismic velocity models into effective viscosity models.
- Organize an effort to benchmark 3D GIA modeling approaches, similar to the benchmarking exercise done a few years ago for 1D codes.
- Encourage the completion of ongoing Activities from 2015-2019 that were approaching completion as of the last report (*Shfaqat Abbas Khan* and *Matt King*, leaders):
  - establish and publish a list of PSMSL tide gauges that are subject to large, time-variable elastic deformation associated with present-day glacier mass

change,

- o compile a database of predictions for relative sea level changes at tide gauges, gravity field, and 3D deformation rates at geodetic sites and on global or regional grids for a set of reasonable GIA models, both for the deglaciation after LGM and more recent ice changes. While this database may not lead to consensus about the "best" model, it will clarify the range of predictions made by models that have some support within the broader community.

SC 3.5: Seismogeodesy (joint with IASPEI)

Chair: *Jean-Mathieu Nocquet* (France)
Vice-Chair: *Takuya Nishimura* (Japan)
Position replacement every 2 years.

Terms of Reference

Space and terrestrial geodetic techniques provide key observations to investigate a broad range of geophysical processes, thanks to their high accuracy, precision, and reliable georeferencing. Thanks to the technological evolution witnessed in the past decades, crustal movements of few millimeters can be now detected and monitored over time, opening new prospects for the study of Earth kinematics and geodynamics.

Among their many applications, geodetic measurements can now contribute to the study of the different phases of the seismic cycle, as they allow recording static and dynamic displacements during large earthquakes, as well as the slow postseismic and interseismic deformation. However, the foundation for fully exploiting the potential of geodetic measurements is the development of a multidisciplinary approach to their interpretation.

The joint IAG-IASPEI SC on Seismogeodesy aims to facilitate the cooperation between the geodetic and the seismological communities to improve our current understanding of the different seismic processes. The investigated phenomena range from large destructive events, to slow earthquakes and tremors. The works of the SC focus on both theoretical aspects and observational challenges. Particular effort is dedicated to identifying gaps of knowledge and opportunity for progress, particularly in the field of hazard assessment and early warning systems.

Objectives

Objectives of SC 3.5 include:

- to actively encourage the cooperation between all geoscientists studying the plate boundary deformation zones, by promoting the exploitation of synergies between different fields;
- to reinforce joint and integrated geodetic and seismological monitoring of seismically active areas by increasing and/or developing infrastructures dedicated to broadband observations from the seismic wave band to the permanent displacement;
- to be a reference group for the integration of the most advanced geodetic and geophysical techniques by developing consistent methodologies for data reduction, analysis, integration, and interpretation;
- to act as a forum for discussion and scientific support for international geoscientists investigating the kinematics and mechanics of the plate boundary deformation zone;
- to promote the use of standard procedures for geodetic data acquisition, quality evaluation, and processing, particularly GNSS data and InSAR data;
- to promote earthquake geodesy, the study of seismically active regions with large earthquake potential, and geodetic application to early warning system of earthquakes and tsunamis for hazard mitigation;
- to promote the role of geodesy in tectonic studies for understanding the seismic cycle, transient and instantaneous deformation, and creeping versus seismic slip on faults.

Program of Activities

- Building on the experience of the WEGENER Initiative, to continue as a framework for geodetic cooperation in the study of the plate boundary zones.
- To develop scientific programs in earthquake geodesy for subduction zones and possible occurrence of giant earthquakes and associated tsunamis.
- To foster the use of space-borne, airborne, marine and hybrid techniques such as GNSS, LIDAR, GNSS-Acoustic, seafloor pressure gauges, radar, optical, and gravity satellite missions including GOCE, GRACE, ENVISAT, SENTINELLE, ALOS, etc. for earth observation.
- To define effective integrated observational strategies for these techniques to reliably identify and monitor crustal movements and gravity variations over all time scales.
- To facilitate and stimulate the integrated exploitation of data from different techniques in the analysis and interpretation of geo-processes.

- To organize periodic workshops and meetings with special emphasis on interdisciplinary research and interpretation and modeling issues.
- To organize special sessions at international meetings.
- To publish the outcome of the researches, either as stand-alone publications or as proceedings or special issues of scientific journals.

Joint Study Group 3.1: Geodetic, Seismic and Geodynamic Constraints on Glacial Isostatic Adjustment

(joint with IASPEI and IAG Commissions 1 and 2)

Chair: *Rebekka Steffen* (Sweden)
Vice-Chair: *Erik R. Ivins* (USA)

Terms of Reference

The solid Earth's memory of past glacial loading has been modelled throughout the past 100 years using much of the same formalism and attention to Earth structure that is found in the study of surface wave seismology. Glacial Isostatic Adjustment (GIA) models and geodynamics models use, as fundamental source of data, both seismologically based internal mantle structure models and geodetic time series. It is therefore the focus of this working group to allow cross fertilization of models, data and conceptual frameworks of these two communities, geodynamics and GIA, with the development of an interdisciplinary approach to better determination of the Earth's internal rheological structure.

The compatibility of the spatial and time scales over which rheological frameworks operate effectively is essential. This JSG shall also task itself with analysis of the currently applied GIA modelling parametrizations, data constraints and emerging geodetic data sets, such as GPS, gravity change, and both relative and absolute sea-level variations. In this interdisciplinary study it will be essential to improve the operative definition of the lithosphere.

We seek to identify critical assessments that can be performed to more tightly constrain the relationships between effective mantle viscosity for use in geodynamics and GIA models that are compatible with the results of advanced seismic imaging of 3-D mantle structure and geodetic time series. Consequently, this Study Group is joined between Commission 1 on Reference Frames, Commission 2 on Gravity Field and Commission 3 on Earth Rotation and Geodynamics with promising cooperation with IASPEI Commission on Earth Structure and Geodynamics.

Objectives

Objectives of JSG 3.1 include:

- to review the integration of geophysical, seismological, and geodynamical modelling as well as fundamental mineral physics into GIA models, with a special emphasizes on their model results (including gravity changes and GNSS rates);
- to formulate general principles for defining the lithosphere for GIA models and assessment of the rheological principles and geophysical observables relevant to that definition;
- to study the relative merits of GIA data types. These data types include GNSS horizontal and vertical motion, tide gauges, gravity changes, observed with both terrestrial and space, techniques, and seismicity, in form of paleo, historic and recent earthquakes. These data are especially powerful when combined with one another. Special emphasis should be placed on evaluating the spatial distribution of data and the length of time series required for GIA modelling;
- to assess the role of GIA model impact on products derived from modern space gravimetry (GRACE) for both ocean and hydrological sciences;
- to intercompare model based transient response of postseismic relaxation following $M_w > 7.0$ earthquakes to the constitutive laws assumed valid in GIA models;

Program of Activities

- Organize a workshop discussing the objectives from above.
- Publishing a report on the definition of the GIA lithosphere.
- Organization of an international joint workshop in 2021 or 2022 (possibly in collaboration with SC 3.4 "Cryospheric Deformation", with JSG 0.21 "Dynamic modeling of deformation, rotation and gravity field variations", and even further related IAG (and IASPEI) working groups).
- Contribution to international meetings and conferences (e.g., EGU, AGU).
- Organization of a session at the IUGG meeting in Berlin in 2023.
- Common publications by JSG members.
- Managing a website with updates on the development of the JSG.

Members

Kristel Chanard (France)
Mark Hoggard (USA)
Paula Koelemeijer (UK)
Tanghua Li (Singapore)
Glenn Milne (Canada)
Bart Root (Netherlands)

Andrew Schaeffer (Canada)
Kate Selway (Australia)
Bernhard Steinberger (Germany)
Doug Wiens (USA)

Joint Working Group 3.1: Improving Theories and Models of the Earth's Rotation

(joint with IAU)

Chair: *José Ferrándiz* (Spain)
Vice-Chair: *Richard Gross* (USA)

Terms of Reference

The main purpose of this JWG is proposing consistent updates of the Earth rotation theories and models and their validation. The associated tasks will thus contribute to the implementation of the 2018 IAU Resolution B1 on Geocentric and International Terrestrial Reference Systems and Frames, and the 2019 IAG Resolution 5 on Improvement of the Earth's Rotation Theories and Models. The last resolution is the most specific for the WG assignment and mandates:

- to encourage a prompt improvement of the Earth rotation theory regarding its accuracy, consistency, and ability to model and predict the essential EOPs;
- that the definition of all the EOPs, and related theories, equations, and ancillary models governing their time evolution, must be consistent with the reference frames and the resolutions, conventional models, products, and standards adopted by the IAG and its components;
- that the new models should be closer to the dynamically time-varying, actual Earth, and adaptable as much as possible to future updating of the reference frames and standards.

The work will be performed in close cooperation other IAG components, particularly GGOS, the IERS, and current WGs dealing with the Earth rotation and standards from specific perspectives, as well as with the IAU Commissions A2 and A3. Continuous coordination will be sought through common members and correspondents.

Program of Activities

At short term, intended as two years in this context, the JWG is committed to derive supplementary models for the Celestial Pole Offsets (CPO) evolution, in part of semi-empirical and semi-analytical nature, and able to increase significantly the explained variance of the current theories and models.

According to the recommendations of the 2019 GGOS-IERS Unified Analysis Workshop, the priority tasks of building such models will include:

- updating the amplitudes of the leading nutations of the IAU2000 theory and testing shortened series for certain operational purposes;
- correcting the inconsistencies found in the precession-nutation models;
- test the available FCN models (for explaining CPO variance) and consider whether the IERS should recommend FCN models or not.

The two years term being too short to develop and publish a fully dynamically consistent theoretical approach to support those models, that activity will likely continue till the end of the term. Theoretical developments must also address to advancing in all the aspects made explicit on resolution 5, like using a consistent framework for all the Earth Orientation Parameters, with regard to reference systems and frames, background models, standards, and adaptation of the developments to the current knowledge of the dynamic Earth, from its inner components to its outer layers. The chairing people may assign specific tasks with delimited scopes to volunteer members and correspondents, according to their expertise, availability and initiative.

Structure and operation

Taking into account the different methods and expertise required for the treatment of the different kinds of EOP and that their theoretical treatment must be as consistent as their determination from observations, we propose to structure the JWG in three Sub-WGs, which should work in parallel for the sake of efficiency. To guarantee that the SWGs are linked together as closely as the needs of consistency demand, the Chair and Vice-Chair of the WG, Ferrándiz and Gross, will be involved in all SWGs as will the President of the IAU Commission A2, F. Seitz, and the Vice-president of IAG Commission 3, C. Huang. Besides, a number of people will be affiliated to more than one SWG.

1. Precession/Nutation
Chair: *Alberto Escapa* ((Spain)
Members:
T. Baenas (Spain),
W. Chen (China),
V. Dehant (Belgium),
C. Huang (China),
J. Vondrak (Czech Republic)
Correspondents:
D. Angermannn (Germany),
C. Bizouard (France),
N. Capitaine (France),
J. Getino (Spain),
J. Hilton (USA),
G. Kaplan (USA),
J.C. Liu (China),

J.F. Navarro (Spain),
J. Ray (USA),
R. Ray (USA),
C. Ron (Czech Republic),
H. Schuh (Germany),
F. Seitz (Germany),
W.B. Shen (China),
D. Thaller (Germany).

2. Polar Motion and UT1
Chair: *Aleksander Brzezinski* (Poland)
Members:
S. Böhm (Austria),
B.F. Chao (Taipei),
J. Nastula (Poland),
F. Seitz (Germany),
W.B. Shen (China).
Correspondents:
D. Angermann (Germany),
C. Bizouard (France),
W. Chen (China),
R. Dill (Germany),
H. Dobslaw (Germany),
L. Fernández (Argentina),
Z. Malkin (Russia),
J. Ray (USA),
D. Salstein (USA),
H. Schuh (Germany),
J. Vondrak (Czech Republic),
L. Zotov (Russia)

3. Numerical Solutions and Validation
Chair: *Robert Heinkelmann* (Germany)
Members:
S. Belda (Spain),
C. Bizouard (France),
Z. Malkin (Russia),
M. Schindelegger (Austria),
B. Soja (USA).
Correspondents:
D. Angerman (Germany),
B.F. Chao (Taipei),
W. Chen (China),
J. Hilton (USA),
J. Mueller (Germany),
J. Ray (USA),
H. Schuh (Germany),
F. Seitz (Germany),
D. Thaller (Germany),
M. Thomas (Germany),
P. Zhu (Belgium).

JWG 3.2: Global combined GNSS velocity field (joint IAG Commissions 1 and 2)

Chair: *Alvaro Santamaría-Gómez* (France)
Vice-Chair: *Roelof Rietbroek* (Germany)

Terms of Reference

This Working Group aims at combining and comparing available GNSS velocity fields obtained by different groups from both network and PPP solutions. It continues the activities of former JWG3.2 "Constraining vertical land motion of tide gauges" with the inclusion of the last reprocessed solutions derived or related to the ITRF2020 realization while also extending the scope to the horizontal component of the velocity field.

GNSS velocities estimated by different groups usually differ due to the choices made concerning the GNSS data processing (corrections applied and noise level of the series), the completeness of the series, the removed position discontinuities and the alignment to a terrestrial reference frame. The position discontinuities that populate the GNSS time series have probably the biggest impact on the velocity estimates. Even when using exactly the same series, it is common that different groups provide different velocity estimates and uncertainties mainly due to the different choices of position discontinuities.

The main outcome of the Working Group will be a combined velocity field that takes into account the repeatability of the estimates by the different groups. It is expected that the combined GNSS velocity field will be useful for the scientific community in the areas of tectonics, sea-level change and GIA modeling among others.

The differences of the combined GNSS velocity field with respect to velocity fields obtained from other techniques (other space geodetic techniques, TGs, satellite altimetry) will be assessed. For instance, differences between tide gauge records and between tide gauges and satellite altimetry can provide constraints on the vertical velocities at the tide gauges. Observations from gravimeters, InSAR and other space geodetic techniques (e.g., DORIS) have the potential to provide valuable information on the velocities.

Program of Activities

- Collect velocity fields from GNSS and other techniques.
- Combine the GNSS velocity fields.
- Assess the differences between the combined GNSS velocity field and other velocity fields.

Members

Thomas Frederikse (USA),
Paul Rebischung (France).

Commission 4 – Positioning and Applications

President: **Allison Kealy** (Australia)
Vice President: **Vassilis Gikas** (Greece)

https://com4.iag-aig.org/

Terms of Reference

IAG Commission 4 intends to bring together scientists, researchers and professionals dealing with the broad area of positioning and its applications. For this purpose, it will promote research that leverages current and emerging positioning techniques and technologies to deliver practical and theoretical solutions for GNSS smartphone positioning technologies, multi frequency, multi constellation GNSS, positioning integrity and quality, alternatives and backups to GNSS, sensor fusion, atmospheric sensing, modelling, and applications based on geodetic techniques. Commmission 4 will carry out its work in close cooperation with the IAG Services and IAG entities, as well as via linkages with entities within scientific and professional organizations.

Recognizing the central role of Global Navigation Satellite Systems (GNSS) in providing the positioning requirements today and into the future, Commission 4 will focus on research for improving models and methods that enhance and assure the positioning performance of GNSS-based positioning solutions for an increasing diversity of end-user applications. It also acknowledges the increasing levels of threat and vulnerabilities for GNSS only positioning and investigates technologies and approaches that address these.

The Sub-Commissions will develop theory, strategies and tools for modeling and/or mitigating the effects of interference, signal loss and atmospheric effects as they apply to precise GNSS positioning technology. They will address the technical and institutional issues necessary for developing backups for GNSS, integrated positioning solutions, automated processing capabilities and quality control measures.

Commission 4 will also deal with geodetic remote sensing, using Synthetic Aperture Radar (SAR), Light Detection and Ranging (LiDAR) and Satellite Altimetry (SA) systems for geodetic applications.

Additional WGs and SGs can be established at any time, and existing can be dissolved, if they are inactive.

Objectives

The main topics dealt by Commission 4 are as listed in the IAG By-laws:

- Terrestrial and satellite-based positioning systems development, including sensor and information fusion;
- Navigation and guidance of platforms;
- Interferometric laser and radar applications (e.g., Synthetic Aperture Radar);
- Applications of geodetic positioning using three dimensional geodetic networks (passive and active networks), including monitoring of deformations;
- Applications of geodesy to engineering;
- Atmospheric investigations using space geodetic techniques.

Structure

Sub-Commissions

SC 4.1: Emerging Positioning Technologies and GNSS Augmentation
Chair: Laura Ruotsalainen (Finland)
SC4.2: Multi-frequency Multi-constellation GNSS
Chair: Suelynn Choy (Australia)
SC 4.3: Atmosphere Remote Sensing
Chair: Michael Schmidt (Germany)
SC 4.4: GNSS Integrity and Quality Control
Chair: Pawel Wielgosz (Poland)

Joint Study Groups

JSG T.32: High rate GNSS
Chair: *Mattia Crespi* (Italy)
(joint with ICCT, description see ICCT)
JSG T.24: Integration and co-location of space geodetic observations and parameters

Chair: *Krzysztof Sośnica* (Poland)
(joint with ICCT, description see ICCT)
JSG T.31: Multi-GNSS theory and algorithms
Chair: *Amir Khodabandeh* (Australia).
(joint with ICCT, description see ICCT)

Steering Committee

President: *Allison Kealy* (Australia)
Vice President: *Vassilis Gikas* (Greece)

Chair SC4.1: *Laura Ruotsalainen* (Finland)
Chair SC4.2: *Suelynn Choy* (Australia)
Chair SC4.3: *Michael Schmidt* (Germany)
Chair SC4.4: *Paweł Wielgosz* (Poland)
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IVS: *Robert Heinkelmann* (Germany)
IGS: *Sharyl Byram* (USA)

Representative of External Bodies

ISPRS: *Charles Toth* (USA)
FIG: *Allison Kealy* (Australia)
ION: *Larry Hothem* (USA)

Sub-Commissions

SC 4.1: Emerging Positioning Technologies and GNSS Augmentations

Chair: *Laura Ruotsalainen* (Finland)
Vice-Chair: *Ruizhi Chen* (China)

Terms of Reference

The global availability of position, velocity and time information due to the maturation of GNSS technologies is creating an increasing demand for more and more accurate and reliable solutions for navigation in also GNSS challenging areas.

At present, navigation is mainly based on the use of Global Navigation Satellite Systems (GNSS), providing good performance in open outdoor environments. However, navigation solution with sufficient accuracy and integrity is needed in urban canyons and indoors, where GNSS is significantly degraded or unavailable. For overcoming the aforementioned navigation challenges, research has been very active for decades for finding a suitable set of other methods for augmenting or replacing the use of GNSS in positioning. As well, safety critical applications such as navigation of autonomous systems require use of multiple technologies.

The SC 4.1 focuses on research using specific technologies, like computer vision for navigation or use of 3D point clouds for situational awareness, platforms like smartphones with low-cost positioning sensors, fusion of multi-sensor measurements and applications such as autonomous systems and localization at urban canyons.

Objectives

- Developing methods for multi-sensor navigation
- Studying and solving navigation problems for safety critical applications such as autonomous driving.
- Formation of 3D point clouds for spatio-temporal monitoring
- Development of computer vision technologies for navigation
- Use of smartphone as a positioning platform
- Localization in deep urban canyons

Program of activities

- To promote research collaboration among groups from geodesy and other branches worldwide dealing with emerging positioning research and applications
- To organize and/or participate in scientific and professional meetings (workshops, conference sessions, etc.)
- To maintain a web page concatenating the Sub-Commission activities and reports
- To encourage special issues on research, applications, and activities related to the topics of this Sub-Commission
- Close co-operations with other elements of the IAG structure and other international organizations such as FIG , ION and ISPRS

Overview of Joint Study Groups (JSG) and Working Groups (WG) of the SC 4.1

- WG 4.1.1 Multi-Sensor Systems
- WG 4.1.2 Autonomous Navigation for Unmanned Systems
- WG 4.1.3 3D Point Cloud based Spatio-temporal Monitoring
- WG 4.1.4 Computer Vision in Navigation
- WG 4.1.5 Localization at Asian urban canyons
- SSG 4.1.1 Positioning using smartphones

WG 4.1.1: Multi-Sensor Systems

Chair: *Allison Kealy* (Australia)
Vice-Chair: *Gunther Retscher* (Austria)

Description

This group is a joint working group between IAG and FIG. It focuses on the development of shared resources that extend our understanding of the theory, tools and technologies applicable to the development of multi-sensor systems.

Objectives

The group has a major focus on:

- performance characterization of positioning sensors and technologies that can play a role in augmenting core GNSS capabilities,
- theoretical and practical evaluation of current algorithms for measurement integration within multi-sensor systems,
- the development of new measurement integration algorithms based around innovative modeling techniques in other research domains such as machine learning and genetic algorithms, spatial cognition etc.,
- establishing links between the outcomes of this WG and other IAG and FIG WGs (across the whole period),
- generating formal parameters that describe the performance of current and emerging positioning technologies that can inform IAG and FIG members.

Specific projects to be undertaken include:

- international field experiments and workshops on a range of multi sensor systems and technologies.
- evaluation of UAV capabilities and the increasing role of multi-sensor systems in UAV navigation.
- investigation of the role of vision based measurements in improving the navigation performance of multi-sensor systems.
- development of shared resources to encourage rapid research and advancements internationally.

Members

N/A

WG 4.1.2: Autonomous Navigation for Unmanned Systems

Chair: *Ling Pei* (China)
Vice-Chair: *Giorgio Guglieri* (Italy)

Description

Unmanned systems (e.g., UAV, driverless vehicles, and robots) have become increasingly important for data acquisition in numerous geospatial applications. In recent years, technological advancements have facilitated the manufacturing of various types of intelligent sensors, such as cameras, LiDAR, motion, wireless, magnetic, light, and ultrasonic ones. These sensors and their enabling multi-sensor autonomous systems have potential to be promoted into the geospatial world such as autonomous vehicles, robotics, smart cities, geolocation, condition monitoring, and context awareness.

The Working Group will focus on the challenges for autonomous navigation using unmanned systems. Although extensive research efforts have been paid to sensors, algorithms, architectures, and applications of unmanned systems, it is still challenging to establish smart, autonomous, and disruptive implementations. Examples of the challenges include enabling robust navigation data acquisition in challenging environments, using crowdsourcing techniques to generate and use multi-source navigation databases, designing low-cost low-power autonomous navigation systems, and cloud and edge computation of multi-sensor navigation data, etc.

Objectives

The group has a major focus on:

- Specification, characterization, and evaluation of the autonomous navigation system requirements in various scenarios
- Technological challenges and emerging applications of UAVs
- New sensors, platforms, and sensors for unmanned vehicle navigation
- Regulations and social impacts on unmanned vehicles
- Scalable multi-sensor integration architectures and technologies for unmanned vehicles
- Self-improving and adaptive navigation systems
- Location-based interactive between autonomous vehicles and human
- Artificial intelligent techniques for environment perception, awareness, data processing, and decision making in unmanned vehicles
- Advanced computation techniques in autonomous navigation systems

Specific projects to be undertaken include:

- Specification, characterization, and evaluation of the system requirements
- Optimal set of sensors and technologies for robust unmanned navigation

- Advantages, challenges, analysis, and application of selected systems
- Relation between autonomous navigation and existing navigation applications
- Relation between autonomous vehicles and human
- Adaptation of navigation sensors and algorithms in various environments

Members

You Li (Canada)
Laura Ruotsalainen (Finland)
Margarida Coelho (Portugal)
Marko Ševrović (Croatia)

WG 4.1.3: 3D Point Cloud Based Spatio-Temporal Monitoring

Chair: *Jens-Andre Paffenholz* (Germany)
Vice-Chair: *Corinna Harmening* (Austria)

Description

The WG will focus on spatio-temporal monitoring of artificial and natural objects with the aid of 3D point clouds acquired by means of multi-sensor-systems (MSS). The emphasis will primarily be placed on laser scanning technology and to a certain extent on digital cameras, satellite and ground-based synthetic aperture radar (GB-SAR). In general, monitoring applications over a certain period of time require a geo-referencing of the acquired data with respect to a known datum. In addition, a kinematic MSS requires the determination of the time-dependent seven degrees of freedom (translation, rotation and scale) with regard to a referencing. Both aforementioned key facts will be included in the WG themes.

Objectives

The group has a major focus on:

- Data evaluation, algorithm development in the direction of meaningful comparison of 3D point clouds of different epochs/measurement times (similar to classical deformation monitoring)
- Evaluate the object's abstraction for epochal comparison by means of discrete point-wise, area-based and shape-based approaches. One suitable method to investigate will be B-spline surfaces.
- Investigate and develop suitable algorithms for change tracking/detection and deformation analysis over time in 3D point clouds for instance by means of feature point tracking or shape matching.
- Evaluate the fusion of heterogeneous data like 3D point clouds and ground-based synthetic aperture radar (GB-SAR) data with respect to structural health monitoring applications of, e.g., infrastructure buildings.
- Algorithms will be implemented in Python, Matlab, C++ and for basic 3D point cloud operations open source libraries, e.g., point cloud library (PCL) will be used.

Specific projects to be undertaken include:

- Strengthen the international visibility by cooperating with FIG Commission 6, e.g. at the FIG Working Week 2020 (The Netherlands, Amsterdam), 10 - 14 May 2020
- Corinna is the Co-Chair of FIG Commission 6 and thus stands for the perfect link between both organisations and their WGs
- A session with up to 6 contributions in the frame of WG is already set up
- Motivate people/network to contribute, e.g., by ResearchGate, Linkedin
- ISPRS laser scanning community, in particular, Marco Scaioni (Italy), Roderik Lindenbergh; the WG tries to be present at the upcoming ISPRS Congress in Nice in June 2020.
- Establish, verify and provide reference and benchmark data sets for 3D Point Cloud Based Spatio-Temporal Monitoring via an open access internet platform

Members

Michele Crosetto (Spain)
Petra Helmholz (Australia)
Christoph Holst (Germany)
Florian Schill (Germany)

Further members will be actively acquired by an email call as well as within the special session “3D point cloud based spatio-temporal monitoring” at the FIG Working Week 2020 in Amsterdam, where the first WG 4.1.3 face-to-face meeting will take place.

WG 4.1.4: Vision Aided Positioning and Navigation

Chair: *Andrea Masiero* (Italy)
Vice-Chair: *Kai-Wei Chiang* (China)

Description

The Work Group will focus on the integration of visual information with other sensor measurements in order to enhance navigation in challenging working conditions, such as indoors and urban canyons. The goal is that of compensating for the degradation of GNSS positioning performance, providing a robust positioning solution in a wide range of conditions, both indoors and outdoors. The WG will take into consideration several cases of interest, focusing in particular on pedestrian navigation, unmanned aerial vehicles, and terrestrial vehicles in urban environments.

In particular, the Work Group focuses on:

- Specifications of the system performance requirements to satisfy usability conditions for the considered case studies.
- Assessment of the usability of vision for aiding navigation in the different case studies, including the investigation of suitable integration methods of other sensors such as TOF cameras and LiDAR.
- Selection of best algorithms and technologies for integrating sensor information and fulfilling the system requirements.
- Analysis of the system performance for all the considered cases in different operating conditions.

Specific projects to be undertaken include:

- Reporting on the system requirements for ensuring usability conditions in the considered cases
- Reporting on the most suitable algorithms for integrating visual information in the considered case studies
- Reporting on the performance analysis of the system
- Reporting on criticalities and potential issues in the developed solution
- Establishing links between the outcomes of this WG and other IAG, FIG and ISPRS WGs addressing sensor fusion for enhancing positioning and navigation results in challenging operating conditions.

Members

Vassilis Gikas (Greece)
Harris Perakis (Greece)
Paolo Dabove (Italy)
Laura Ruotsalainen (Finland)
Rui Alexandre Matos Araujo (Portugal)
Vincenzo Di Pietra (Italy)

WG 4.1.5: Positioning and Navigation in Asian Urban Canyons

Chair: *Li-Ta Hsu* (Hong Kong)
Co-Chair: *Kubo Nobuaki* (Japan)

Background

This group is a joint working group between IAG and ION. Accurate positioning and localization in urban canyons remain a challenging problem for systems with navigation requirements, such as autonomous driving vehicles (ADV) and unmanned aerial vehicles (UAV). The urban canyons are typical in megacities like Hong Kong and Tokyo. The globally referenced GNSS positioning can be significantly degraded in urban canyons, due to the blockage from tall buildings.

The visual positioning, LiDAR positioning can be considerably affected by numerous dynamic objects. To facilitate the development and study of robust, accurate and safe positioning solutions in urban canyons with multiple sensors, we form a working group to jointly build an integrated dataset collected in diverse challenging urban scenarios in Hong Kong and Tokyo that provides full-suit sensor data, which includes GNSS, INS, LiDAR and cameras.

Locations for data collection

Urban canyons in Tokyo, Japan, and Hong Kong, which we believe are the most challenging positioning areas in the city environments.

Objectives

- Open-sourcing localization sensor data, including GNSS, INS, LiDAR and cameras collected in Asian urban canyons, including Tokyo and Hong Kong.
- Raising the awareness of the urgent navigation requirement in highly-urbanized areas, especially in Asian-Pacific regions.
- Providing an integrated online platform for data sharing to facilitate the development of navigation solutions of the research community.
- Benchmarking positioning algorithms based on the open-sourcing data.

Specific projects to be undertaken include:

- Proposing a special session on “Positioning and Navigation in Asian Urban Canyons” in ION Pacific PNT 2021. These chairs of the session will disseminate the dataset and encourage the researcher to make use of this open-sourcing data to present in the session.
- Disseminating the open-source dataset in the major academic conferences that related to positioning and navigation.
- Identifying the experts in the field to design the assessment criteria for different positioning algorithms. Positioning methods such as GNSS SPP, PPP, RTK and 3D mapping aided (3DMA) GNSS will be considered in the first stage. Then, GNSS/INS integration and LiDAR, visual odometry will be considered in the second stage. Finally, the multi-sensor integration using all the sensors will be considered.
- Building a website to let the researchers upload their paper and result that evaluated based on the open-source data in terms of the proposed criteria.

- Reporting the performance of the state-of-the-art positioning and integration algorithms in the urban canyons every 2 years.
- Identifying the challenges of using different sensors in urban canyons.

Members

Junichi Meguro (Japan)
Taro Suzuki (Japan)
Wu Chen (Hong Kong)
Zhizhao Liu (Hong Kong)

SG 4.1.1: Positioning Using Smartphones

Coordinators: *Gunther Retscher* (Austria), *Ruizhi Chen* (China)

Terms of Reference (ToR)/Description

With the increasing ubiquity of smartphones and tablets, users are now routinely carrying a variety of sensors with them wherever they go. These devices are enabling technologies for ubiquitous computing, facilitating continuous updates of a user's context. They have built-in GNSS (Global Navigation Satellite Systems), Wi-Fi (Wireless Fidelity), Bluetooth, cameras, MEMS-based inertial sensors, etc. Sensor fusion techniques are required to enable robust positioning and navigation in complex environments needed by consumer users, vehicles, and pedestrians. The SG will be dealing with current developments of such technologies and techniques.

Objectives

Within the next four years we will focus on:

- Specification, characterization, and evaluation of smartphone positioning and navigation system requirements
- Emerging technologies and techniques and their usage
- Absolute and relative positioning technologies and techniques
- Usage of signals-of-opportunity from different systems, such as Wi-Fi, Ultra-wide Band (UWB), Bluetooth iBeacons, etc.
- Inertial MEMS-based sensors positioning and their integration
- Vision-based positioning with smartphone cameras
- Development of robust sensor fusion algorithms

Members

Brian Bai (Australia)
Thilantha Dammalage (Sri Lanka)

SC4.2: Multi-frequency Multi-constellation GNSS

Chair: *Suelynn Choy* (Australia)
Vice Chair: *Sunil Bisnath* (Canada)

Terms of Reference

The year 2020 marks a new era of multi-constellation GNSS with increased number of available satellites in different orbits, diverse signals/frequencies, and new correction products and services. This ongoing modernization offers exciting prospects for further improvement of high precision GNSS PNT and open up new areas of research and innovation.

For example, the increased number of satellites and signals-in-space improves the performance of precise positioning applications; the available of addition frequency signals (beyond L1 and L2) enables new concepts for signal quality assessment and improved carrier phase ambiguity resolution techniques; multi-GNSS satellite metadata to allow determination of GNSS-based terrestrial reference frame scale, orbit determination; as well as new services such as Precise Point Positioning (PPP) and emergency warning services.

Recognizing the central role of GNSS in enabling high precision PNT, SC4.2 will foster research to address interoperability of high precision GNSS, which includes standards, theory, algorithms development and applications of multi-GNSS. In addition, SC4.2 will encourage research in emerging areas such as carrier phase positioning and ambiguity resolution for mass-market GNSS positioning; as well as GNSS PNT and LEO constellation.

SC4.2 will coordinate activities to promote and deliver practical and theoretical solutions for engineering and scientific applications and also will stimulate strong collaboration with the IAG Services (IGS) and relevant scientific and professional sister organizations such as FIG, ION and IEEE.

Objectives

The objectives of SC4.2 are:

- Identify and investigate important scientific and technical issues in multi-frequency multi-constellation GNSS
- Encourage international collaboration in new areas of research and innovation
- Promote interoperability and compatibility of GNSS
- Promote development of GNSS applications in the Asia Pacific region and contribute to capacity building of GNSS education and training

- Encourage partnerships across research, government and industry on applications of multi-frequency multi-constellation GNSS

WG 4.2.1: Interoperability of GNSS precise positioning (Joint WG between IAG and IGS)

Chair: *Allison Kealy* / *Suelynn Choy* TBA (Australia)
Vice-Chair: *Sharyl Byram* (USA)

Objective

To promote interoperability of GNSS precise positioning to support a wide range of science and engineering applications which will benefit society. Activities include:
(1) encourage sharing and dissemination of knowledge of satellite parameters and receiver properties which are essential for high precision GNSS applications; and
(2) investigate new techniques and algorithms to ensure interoperability of correction products for precise point positioning (PPP).
This WG will work in close scientific collaboration with IGS, FIG and ICG.

WG 4.2.2: Ambiguity resolution for low-cost GNSS positioning

Chair: *Xiaohong Zhang* (China)
Vice-Chair: *Robert Odolinski* (New Zealand)

Description

In the past few decades the American GPS and Russian GLONASS have been the dominant satellite systems in Geodesy and Geophysics applications. Recent developments in Global Navigation Satellite Systems (GNSSs) involve the Chinese BeiDou Navigation Satellite System (BDS), Japanese Quasi-Zenith Satellite System (QZSS), European Galileo, and modernization of triple-frequency GPS and GLONASS signals.

Through the many more line of sights and frequencies obtained in a combined multi-GNSS model, one can improve the positioning reliability and accuracy when compared to using any of the satellite systems separately. The challenges lie however in formulating rigorous models and algorithms to link these satellite observations to the parameters of interests.

Low-cost multi-GNSS receiver development has taken a revolutionary role in precise positioning applications in the past few years. By combining several GNSSs, it has been demonstrated that a competitive low-cost positioning performance can be obtained to that of using survey-grade GNSS receivers and antennas. Smartphone manufacturers have started to take advantage of such low-cost GNSS chips, which has led to precise positioning applications in smartphones as well. The research conducted will focus on algorithms and methods for integer ambiguity resolution on low-cost handheld devices, to facilitate optimal modelling of precise positions and atmospheric delays (ionosphere and troposphere), to investigate the quality control methods for low-cost GNSS precise positioning, to develop a robust algorithms of integration GNSS with MEMS and other low-cost sensors.

Members

Yang Gao (Canada)
Wu Cheng (China)
Amir Khodabandeh (Australia)
Dinesh Manandhar (Japan)
Nacer Naciri (Canada)
Baocheng Zhang (China)

WG 4.2.3: GNSS and LEO constellation

Chair: *Xingxing Li* (Germany)
Vice-Chair: *Safoora Zaminpardaz* (Australia)

Description

There has been significant development in building large LEO constellations of satellites to provide a positioning, navigation and timing service. These LEO constellations give us a great opportunity to create new LEO-augmented GNSS technologies and applications, and even to open up new research areas. However there are many challenges. This WG is devoted to promote research, develop models and algorithms, and study theoretical and practical foundations for LEO-augmented GNSS technologies. The main research focus will include, but not limited to, LEO-augmented GNSS precise positioning with rapid convergence, integrated precise orbit determination, LEO-GNSS meteorology and ionospheric sounding methodology, terrestrial reference frame realization, etc. Many efforts will also be made to stimulate strong collaborations among researchers and international organizations.

Members

Bofeng Li (China)
Maorong Ge (Germany)
Oliver Montenbruck (Germany)
Yansong Meng (China)
Xiaohong Zhang (China)

Lang Bian (China)
Denise Dettmering (Germany)
Jan Dousa (Czech Republic)
Inigo del Portillo (USA)
Xiaodong Ren (China)
Tyler G. R. Reid (USA)
Adrian Jäggi (Switzerland)
Qile Zhao (China)
Jose van den Ijssel (Netherlands)
Da Kuang (USA)
Daniel Koenig (Germany)
Wenhai Jiao (China)
Rothacher Markus (Switzerland)
Baoguo Yu (China)

WG 4.2.4: Multi-GNSS in Asia

Chair: *Chalermchon Satirapod* (Thailand)
Vice-Chair: *Hung-Kyu Lee* (Korea)

As the Asia Oceania GNSS downstream market continues to grow rapidly, the role of the WG is to further promote GNSS scientific research, development and applications in the region. It will also focus on education and capacity building such as training, research, and networking activities to encourage the next generation of GNSS researchers. The working group will work in close cooperation with Multi-GNSS Asia (MGA) to promote applications of GNSS and SBAS such as in surveying, construction, agriculture, transportation and logistics, as well as emergency response and disaster management.

Members

Toshiaki Tsujii (Japan)
Hyung Keun Lee (Korea)
Ben K.H. Soon (Singapore)
Horng-Yue Chen (China)
Michael Moore (Australia)
Dudy Darmawan (Indonesia)
Trong Gia Nguyen (Vietnam)

SC 4.3: Atmosphere Remote Sensing

Chair: *Michael Schmidt* (Germany)
Vice-Chair: *Ehsan Forootan* (Wales)

Terms of Reference

The Earth's atmosphere can be structured into various layers depending on physical parameters such as temperature or charge state. From the geodetic point of view the atmosphere is nowadays not only seen as a disturbing quantity which has to be corrected but also as a target quantity, since almost all geodetic measurement techniques, such as GNSS, satellite altimetry, VLBI, SLR, DORIS and radio occultations, provide valuable information about the state of and the dynamics within the atmosphere. One up-to-date challenge is to combine all these data efficiently to extract as much information as possible. Space weather events, gravity waves, natural hazards, climate change and autonomous driving are a few modern catchwords in this context.

For many decades the International GNSS Service (IGS) is delivering high-precision tropospheric and ionospheric, i.e. atmospheric products. The Ionosphere Associated Analysis Centers (IAAC), for instance, provide routinely maps of the Vertical Total Electron Content (VTEC), i.e. the integral of the electron density along the height to correct measurements for ionospheric influences, usually disseminated with latencies of days to weeks and based on post-processed observations and final orbits to the user. Precise GNSS applications, however, such as autonomous driving or precision farming, require the use of high-precision and high-resolution atmospheric correction models in real-time. Thus, real-time modelling of the atmosphere is one of the key tasks of the SC 4.3.

Space weather and especially its impacts and risk are gaining more and more importance in politics and sciences, since our modern society is highly depending on space-borne techniques, e.g., for communication, navigation and positioning. Coupling processes between different atmospheric layers and interrelations with climate change are other up-to-date topics. Besides sounding the atmosphere and studying space weather effects by modern evaluation methods, the promising GNSS reflectometry technique (GNSS-R) is another research topic within the SC 4.3.

The SC 4.3 focuses on a coordinated research in understanding processes within and between the different atmospheric layers using space-geodetic measurements and observations from other branches such as astrophysics or heliophysics. Furthermore, it is concentrated on developing new strategies, e.g., for prediction and detection of small and medium atmospheric structures.

Objectives

- Studying and solving problems of atmosphere research for up-to date applications such as autonomous driving.
- Bridging the gaps between modern geodetic observation techniques such as radio occultations or GNSS reflectometry, measurements from other scientific branches such as astrophysics and geophysics with the geodetic community

- Exploration of the synergies between geodesy and other scientific branches such as astrophysics and geophysics
- Investigation of ionosphere phenomena such currents or scintillations
- Support of atmosphere prediction models based on the combination of data from different observation techniques, e.g. by developing sophisticated estimation procedures
- Improvement of precise positioning and navigation on the basis of new atmosphere models
- Development of real- and near real-time techniques for atmosphere monitoring

Program of activities

- To promote research collaboration among groups from geodesy and other branches worldwide dealing with atmosphere research and applications
- To organize and/or participate in scientific and professional meetings (workshops, conference sessions, etc.)
- To maintain a web page concatenating the Sub-Commission activities and reports
- To encourage special issues, e.g. of Journal of Geodesy, on research, applications, and activities related to the topics of this Sub-Commission
- Close co-operations with other elements of the IAG structure, such as IAG Commission 1, the ICCT, the ICCC and GGOS.

Overview about Joint Study Groups (JSG), Working Groups (WG) and Joint Working Groups (JWG) of or related to the SC 4.3

- JWG 4.3.1 Real-time ionosphere monitoring and modelling (joint with IGS and GGOS)
- WG 4.3.2 Prediction of ionospheric state and dynamics
- WG 4.3.3 Ionosphere scintillations
- JWG 4.3.4 Validation of VTEC models for high-precision and high resolution applications (joint with IGS, GGOS and Comm. 1)
- WG 4.3.5 Sensing small-scale structures in the lower atmosphere with tomographic principles
- WG 4.3.6 Real-time troposphere monitoring
- WG 4.3.7 Geodetic GNSS-R
- JSG from other leading commissions joint with Commission 4, SC 4.3:
    - JSG 1 (JSG T.27): Coupling processes between magnetosphere, thermosphere and ionosphere (IAG ICCT, joint with GGOS Focus Area on Geodetic Space Weather Research)
- JWGs from other leading commissions joint with Commission 4, SC 4.3:
    - JWG 1: Electron density modelling (GGOS Focus Area on Geodetic Space Weather Research)
    - JWG 2: Improvement of thermosphere models (GGOS Focus Area on Geodetic Space Weather Research, joint with ICCC)
    - JWG 3: Improved understanding of space weather events and their monitoring by satellite missions (GGOS Focus Area on Geodetic Space Weather Research);
    - JWG 1.x.x: Intra- and inter-technique atmospheric ties (Comm. 1)
    - JWG x: Zenith Total Delays and gradients quality control for climate (ICCC, joint with Comm. 4)

JWG 4.3.1: Real-time ionosphere monitoring and modelling (Joint with IGS and GGOS)

Chair: *Zishen Li* (China)
Vice-Chair: *Ningbo Wang* (China)

Terms of Reference (ToR) / Description

The WG focuses on the methodology development for real-time ionosphere monitoring and modelling with the use of multiple space-geodetic observations, in particular the inclusion of ionospheric observables from the new GNSS constellations (e.g. Galileo and BeiDou), altimetry, DORIS and radio occultation (RO) techniques aside from the ground-based GPS/ionosonde measurements. The approaches for the retrieval of precise ionospheric parameters (e.g. total electron content), generation of two- and/or three-dimensional ionosphere maps on regional and global scales, independent validation and potential combination of ionospheric information from different providers in real-time will be developed and analysed. The dissemination of real-time ionospheric information following RTCM, 5G or other standards will be discussed in support of both scientific researches and technological applications. The connections to IGS, iGMAS, IDS, IRI, NeQuick and other communities will also be involved for the possible establishment of joint WGs or experimental campaigns on real-time ionosphere monitoring.

Objectives

Within the next four years we will focus on:

- close connections to different scientific communities (e.g. IGS, iGMAS and IDS) for the coordination of RT/NRT ground- and space-based measurements in support of real-time ionosphere monitoring.

- comparison of different approaches for real-time ionosphere modelling by the combination of multi-constellation observations with distinct characteristics (e.g. biases and time latencies).
- development of methods for the independent validation and potential combination of real-time ionospheric information from different providers.
- discussions on the distribution of real-time ionospheric information within scientific and technological communities (e.g. target parameter, data format and time latency).
- generation and dissemination of experimental two- and/or three-dimensional ionospheric information in support of real-time ionosphere monitoring and associated scientific applications.
- possible joint sub working groups or experimental campaigns on real-time ionosphere monitoring in close scientific collaboration with IGS and IDS WGs, COSPAR IRI and NeQuick WGs, among others.

Members

Alberto Garcia-Rigo (Spain)
Alexis Blot (France)
Andre Hauschild (Germany)
Andreas Goss (Germany)
Andrzej Krankowski (Poland)
Attila Komjathy (USA)
Cheng Wang (China)
Eren Erdogan (Germany)
German Olivares (Australia)
Kenji Nakayama (Japan)
Libo Liu (China)
Manuel Hernández-Pajares (Spain)
Nicolas Bergeot (Belgium)
Ningbo Wang (China)
Qile Zhao (China)
Raul Orús (Netherland)
Reza Ghoddousi-Fard (Canada)
Wookyoung Lee (Korea)
Xingliang Huo (China)
Yunbin Yuan (China)
Zhizhao Liu (China)
Zishen Li (China)

WG 4.3.2: Prediction of ionospheric state and dynamics

Chair: *Mainul Hoque* (Germany)
Vice-Chair: *Eren Erdogan* (Germany)

Terms of Reference (ToR) / Description

Ionospheric disturbances can affect technologies in space and on Earth disrupting satellite and airline operations, communications networks, navigation systems. As the world becomes ever more dependent on these technologies, ionospheric disturbances as part of space weather pose an increasing risk to the economic vitality and national security. Having the knowledge of ionospheric state in advance during space weather events is becoming more and more important.

With the modernization of Global Navigation Satellite Systems (GNSS), the use of multi-constellation, multi-frequency observations including new signals enables continuous monitoring of the Earth's ionosphere using worldwide distributed sensor stations. Other ground based techniques such as vertical sounding (VS), Incoherent Scatter Radar (ISR), Very Low Frequency (VLF) or Radio Beacon (RB) measurements provide complementary ionospheric observations.

The radio occultation (RO) technique provides one of the most effective space-based methods for exploring planetary atmospheres. The availability of numerous medium Earth orbit satellites deployed by GPS, GLONASS, Galileo, BeiDou navigation systems allows continuous monitoring of the Earth's ionosphere and neutral atmosphere by tracking GNSS signals from low Earth orbiting (LEO) satellites. Other space-based techniques include ionosphere estimation using dual-frequency altimeter data (e.g. TOPEX-Poseidon, Jason 2 & 3 missions), using radio beacon measurements from DORIS (geodetic orbit determination and positioning system) receivers onboard LEO satellites and GNSS reflectometry.

The availability of ionospheric data from different sensors has increased in many folds during the last decades. In one hand the ionosphere has been sounded by a large number of sensors providing a vast database. On the other hand, the accuracy of the measuring techniques has been improved significantly.

As an example, the IGS is routinely generating ionospheric total electron content (TEC) maps from GNSS data since 1998. The inter-dependency of different space weather parameters (e.g., TEC, peak electron density and height, solar flux, geomagnetic indices, interplanetary magnetic field components etc.) paves the way for determining ionospheric prediction algorithm. With the availability of fast computing machines as well as the advancement of the machine learning techniques and Big Data algorithms, the prediction of ionospheric state and dynamics is possible in near real time.

Objectives

Within the next four years we will focus on:

- study the inter-dependency of different space weather parameters (e.g., TEC, solar flux, geomagnetic indices, interplanetary magnetic field components etc.) during quiet and perturbed conditions, trend analysis and algorithm development for predicting space weather parameters
- develop global as well as regional prediction approaches considering that the high latitude phenomena/processes are different from the low latitude phenomena/processes and hemispherical asymmetry (e.g., South Atlantic Anomaly)
- modelling the phenomena which are closely connected to nighttime filling of the ionosphere such as the Nighttime Winter Anomaly (NWA), Weddell Sea Anomaly (WSA) and the Okhotsk Sea Anomaly (OSA). It is assumed that the midsummer nighttime anomaly (MSNA) and related special anomalies such as the WSA and the OSA are closely related to the NWA via enhanced wind-induced uplifting of the ionosphere.

Members

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Enric Monte (Spain)
Fabricio Prol (Germany)
Liangliang Yuan (China)
Ke Su (China)
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Murat Durmaz (Turkey)

WG 4.3.3 Ionosphere scintillations

Chair: *Jens Berdermann* (Germany)
Vice-Chair: *Lung-Chih Tsai* (China)

Terms of Reference (ToR) / Description

Trans-ionospheric radio signals of global navigation satellite systems (GNSS) like GPS, GLONASS, GALILEO and BeiDou may suffer from rapid and intensive fluctuations of their amplitude and phase caused by small-scale irregularities of the ionospheric plasma. Such disturbances occur frequently in the equatorial region during the evening hours due to plasma flow inversion or during geomagnetic storms in the polar region. This phenomenon is called radio scintillation and can strongly disturb or even disrupt the signal transmission.

The main effects of scintillation on trans-ionospheric radio system are signal loss and phase cycle slips, causing difficulties in the signal lock of receivers. All GNSS signals are affected, but the influence of the small scale irregularities is expected to differ since the signals are transmitted by different carrier frequencies and are constructed in different ways. Furthermore, the sensitivity of receivers in respect to scintillation events differ between various GNSS receiver types and an advanced analysis using “bitgrabber” systems are needed to rate their vulnerability.

In spite of the importance of irregular density variations for the science of the ionosphere and for space weather operations, no fully sufficient global model for such disturbances is available.

Objectives

Within the next four years we will focus on:

- understanding the climatology of ionospheric scintillations, namely, its variation with latitude, season, local time, magnetic activity and solar cycle,
- investigation of the GNSS signal frequency and receiver impact on signal loss and phase cycle slips during scintillation events
- global modelling and forecasting of scintillations taking into account temporal and regional (Polar and Equatorial region) differences.

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JWG 4.3.4: Validation of VTEC models for high-precision and high resolution applications (Joint with IGS)

Chair: *Anna Krypiak-Gregorczyk* (Poland)
Vice-Chair: *Attila Komjathy* (USA)

Terms of Reference (ToR) / Description

Global and regional VTEC models are routinely used in Space Weather studies, but also in high-precision applications like e.g. GNSS positioning. There are currently many analysis centers and research groups providing operational and test VTEC maps. Indeed, the global ionospheric maps (GIMs) are being systematically produced and openly provided by the IGS Ionosphere Working Group (IIWG) since 1 June 1998. IGS GIMs are developed as an official product of IIWG by performing a weighted mean of the various Analysis Centers (AC) VTEC maps. There are also important empirical models like the International Reference Ionosphere (IRI) or NeQuick that are based on statistical analysis of the results of measurements.

However, IGS ACs and other groups use different mathematical models and estimation techniques resulting different resolutions, accuracies and time delays of their products. Therefore, there is a need to compare and validate existing VTEC models in order to better understand their performance and quality, and hence to better understand the ionosphere and foster VTEC models usage in geosciences community.

Objectives

Within the next four years we will focus on:

- close connections to different scientific communities – primarily to IGS and GGOS
- comparison of GNSS-derived VTEC maps and empirical models
- VTEC validation with external data, such as altimetry, DORIS, Swarm, radio occultation (RO) and ground-based ionosonde measurements
- VTEC validation is precise GNSS positioning
- development of new validation techniques

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Qi Liu (Spain)
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WG 4.3.5: Real-time Troposphere Monitoring

Chair: *Cuixian Lu* (China)
Vice-Chair: *Galina Dick* (Germany)

Terms of Reference (ToR) / Description

The main objective of this WG is to develop, optimize and assess new real-time or ultra-fast GNSS tropospheric products, and exploit the full potential of multi-GNSS observations in weather forecasting. Tropospheric zenith total delays, tropospheric linear horizontal gradients, slant delays, integrated water vapour (IWV) maps or other derived products in sub-hourly fashion are foreseen for future exploitation in numerical and non-numerical weather nowcasting or severe weather event monitoring.

The use of Precise Point Positioning (PPP) processing strategy will play a key role in developing new products because it is an efficient and autonomous method, it is sensitive to absolute tropospheric path delays, it can effectively support real-time or ultra-fast production, it may optimally exploit data from all GNSS multi-constellations, it can easily produce a full variety of parameters such as zenith total delays, horizontal gradients or slant path delays and it may also support as reasonable as high temporal resolution of all the parameters. Last, but not least, the PPP is supported with the global orbit and clock products provided by the real-time service of the International GNSS Service (IGS).

Objectives

Within the next four years we will focus on:

- development of real-time multi-GNSS processing algorithms and strategies for high-resolution, rapid-update NWP and nowcasting applications.
- development of new/enhanced GNSS tropospheric products and exploit the full potential of multi-GNSS (GPS, GLONASS, Galileo and BeiDou) observations for use in the forecasting of severe weather.

- development and validate methods for initialization of NWP models using new/enhanced operational multi-GNSS tropospheric products and for use in nowcasting.
- assessing the benefit of new/enhanced GNSS products (real-time, gradients, slants…) for numerical and non-numerical nowcasting.
- stimulate the development of application software for supporting routine production.
- demonstrate real-time/ultra-fast production, assess applied methods, software and precise orbit and clock products.
- setup a link to the potential users, review product format and requirements.

Members

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Fabian Hinterberger (Austria)
Eric Pottiaux (Belgium)
Thaleia Nikolaidou (Canada)
Xingxing Li (China)
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Rosa Pacione (Italy)
Yoshinory Shoji (Japan)
Felix Norman Teferle (Luxembourg)
Siebren de Haan (The Netherlands)
Jonathan Jones (United Kingdom)
John Braun (USA)
Galina Dick (Germany)
Tomasz Hadaś (Poland)

WG 4.3.6: Sensing small-scale structures in the lower atmosphere with tomographic principles

Chair: *Gregor Moeller* (Switzerland)
Vice-Chair: *Chi Ao* (USA)

Terms of Reference (ToR)/Description

The working group on troposphere tomography intends to bring together researchers and professionals working on tomography-based concepts for sensing the neutral atmosphere with space-geodetic and complementary observation techniques, sensitive to the water vapour distribution in the lower atmosphere.

While geodetic GNSS networks are nowadays the backbone for troposphere tomography studies, further local densifications, e.g. at airports or cities are necessary to achieve very fine spatial and temporal resolution. Besides, InSAR interferograms, GNSS radio occultation or microwave radiometer profiles are a valuable asset, which can provide the necessary complementary information for stabilizing the tomography system. Furthermore, in the next decade CubeSat missions are expected, which are designed for tomography processing. These constellations can operate independently from ground-based networks and due to a more favourable observation geometry, will allow for sensing globally the water vapour distribution in the neutral atmosphere with increased spatial resolution.

Objectives

Within the next study period (2019-2023), the working group on troposphere tomography intends to address current challenges in tropospheric tomography with focus on space-based measurements using tomography principles. Hereby, the main objectives are:

- Evaluating approaches for the densification of existing dual-frequency geodetic networks;
- Working towards a dynamical tomography model - adaptable to varying input data (continuous-time image reconstruction, trade-off between model resolution and variance size);
- Setting up a benchmark campaign for the combination of ground-based GNSS with radio occultation and other observation techniques like InSAR;
- Assessing existing ray-tracing approaches for the reconstruction of space-based observations;
- Working on standards for data exchange (SINEX TRO 2.0 or other formats).

Members

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WG 4.3.7: Geodetic GNSS-R

Chair: *Sajad Tabibi* (Luxembourg)
Vice-Chair: *Felipe Nievinski* (Brazi)

Terms of Reference (ToR) / Description

The radio waves broadcast by Global Navigation Satellite Systems (GNSS) satellites have been used for unanticipated purposes, such as remote sensing of the environment. The most prominent example for a novel application from recent years is the usage of reflected GNSS signals as a new tool for remote sensing. GNSS Reflectometry (GNSS-R) has been used to exploit signals of opportunity at L-band for ground-based sea and lake level studies at several locations in the last few years. Although geodetic-quality antennas are designed to boost the direct transmission from the satellite and to suppress indirect surface reflections, the delay of reflections with respect to the line-of-sight propagation can be used to estimate the water-surface level in a stable terrestrial reference frame. GNSS-R has started to make an impact in the disciplines of geodesy and remote sensing, with diverse applications such as sea-level, snow depth, and soil moisture monitoring, observations are highly relevant to the goals of the Global Geodetic Observing System (GGOS). Thus, the overall aim of this working group is to further demonstrate and consolidate the value of GNSS-R for the geodesy, oceanography, cryosphere, and hydrology communities.

Objectives

Within the next four years we will focus on:

- identification of GNSS-R products which have a strong relation to IAG services and goals.
- maintain interactions with neighboring societies (such as the IEEE Geoscience and Remote Sensing Society, GRSS) and cooperate with technological, engineering, and operational entities related to GNSS (e.g., the International GNSS Service, IGS), identifying common goals and detecting potential synergies.
- organization of working meetings with GNSS-R experts, while also inviting stakeholders from the geodetic community to participate in such events.
- maintain the GNSS-R site guidelines for installing multi-purpose GNSS stations
- maintain the inventory of GNSS stations used for reflectometry purposes, currently available for sea-level applications, possibly extending it to other applications as well.
- organization of a near-operational demonstration project on GNSS-R for coastal sea level monitoring.
- organization of algorithm inter-comparison exercises. These can be based on either synthetic data or field measured GNSS data. Validation will be based, respectively, on the simulation configuration or independent *in situ* data (e.g., tide gauges for sea level applications). The treatment of external corrections, such as atmospheric effects, should be considered. Challenging conditions should also be addressed, such as large tidal range (~ 4-5 m) and the impact of multi-GNSS revisit time on tidal constituent.

Members

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Overview about Joint Study Groups (JSG), Working Groups (WG) and Joint Working Groups (JWG) led by other IAG components (Commissions, ICCT, ICCC, GGOS)

JWG 1.1.1: Intra- and Inter-Technique Atmospheric Ties

(Led by Commission 1 Reference Frames, joint with Commission 4, Sub-commission 4.3)

Chair: *Kyriakos Balidakis* (Germany)
Vice-Chair: *Daniela Thaller* (Germany)

Terms of Reference (ToR) / Description

The differences between atmospheric parameters (mainly zenith delays and gradients) at co-located stations that observe nearly simultaneously, and stem from external systems (e.g., meteorological sensors or weather models) are understood as atmospheric ties. Atmospheric ties mainly exist because of differences in (i) the observing frequency, (ii) the relative position, and (iii) the observing system set-up.

The acquisition of accurate atmospheric delay corrections is of paramount importance for mm-level positioning employing space geodetic techniques. Atmospheric delay corrections may stem from dedicated instruments such as water vapor radiometers, meteorological sensors, numerical weather models, or from the geodetic data itself. While the latter is fairly common for modern GNSS and VLBI, observation geometry and accuracy limitations inherent to other systems such as SLR and DORIS impede the accurate atmospheric parameter estimation, thus hindering among else positioning.

To this end, it might be useful to compare and combine atmospheric parameters at co-located sites, in a manner similar to the combination of station and satellite coordinates, as well as Earth rotation parameters (via local, space, and global ties, respectively). The multi-technique combination is indispensable to the distinction between real signals and undesired technique-specific artefacts.

Nowadays, the multi- technique combination is facilitated by the increasing investments in state-of-the-art geodetic infrastructure at co-located sites. However, a host of systematic and random errors render the combination via atmospheric ties a difficult task. Moreover, since atmospheric delays are dependent upon essential climate variables (pressure, temperature, and water vapor), differences in long-term atmospheric delay time derivatives at co-located stations might offer an insight into local climate change.

Objectives

The purpose of this working group is to answer the questions:

- How can one relate atmospheric parameter estimates and the time derivatives thereof that refer to different place, time, and observing system? What are the limits in distance, time lag, and observing system?
- What is the optimal way to combine atmospheric parameters?
- Which are the risks from including atmospheric ties in a multi-technique terrestrial reference frame combination?

Specific program activities

Comparison of atmospheric delay estimates from single-technique geodetic analysis (GNSS, SLR, VLBI, and DORIS) Comparison of atmospheric delays from state-of-the-art meso-beta scale weather models (e.g., ERA5 and MERRA2), and high-resolution WRF runs Assessment of spatial and temporal correlation between atmospheric parameters Assessment of multi-technique combination employing atmospheric ties on the single site and global TRF level

Members

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Sośnica Krzysztof (Poland)
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JWG C.2: Quality control methods for climate applications of geodetic tropospheric parameters

(Led by ICCC, joint with Commission 4, Sub-Commission 4.3)

Chair: *Rosa Pacione* (Italy)
Vice-Chair: *Marcelo Santos* (Canada)

Introduction

Zenith Total Delay (ZTD) estimates are determined on a regular basis by several processing centers. For example, the IGS Analysis Centers have all their own independent ZTD solutions but, unlike other estimated parameters (e.g., orbits and satellite clocks) they are not combined. The official IGS ZTD product is the result of an independent and dedicated solution based on a precise point positioning solution. On the other hand, EUREF performs combination of ZTD estimates on a regular basis as well as the IVS, which combines ZTD estimates coming from VLBI sessions. Nonetheless, not all IGS and IVS analysis centers make available their ZTD estimates.

GNSS is reaching the "maturity age" of 30 years when climate normals of ZTD and gradients can be derived. But what would be the best series to serve the climate community? What series would offer the most realistic trends? As the IGS moves towards its third reprocessing campaign (REPRO3) where all ACs are to be make available their own ZTD and gradient estimates, as the IVS is moving towards its ACs also providing ZTD and gradient estimates and as the PPP-derived IGS product continues to be produced, there is a huge opportunity to perform quality control, using the tools of combination of parameters, to assess what would be the ZTD and gradient product best suited to be made available to climate studies.

Objectives

Potential scientific questions include:

- Are there advantages of combining ZTD estimates over not combining them? Is there any 'loss of information' in performing combinations?
- Would there be difference in trends derived from them? If so, how much implication for feeding information to climate?
- Can we trust in a combined ZTD as we trust any combined products (e.g., orbits, clock, site coordinates)?
- What the best combination strategy can be done (not necessarily to combine exactly the same way as other products)?
- Under what criteria can we use spectral analysis to demonstrate that a 'good' combined product have the same properties of the contributing solutions?
- What metrics should be used to ascertain that the optimal set of ZTD estimates, gradients and their trends, are provided to the climate community?

Activities

- Collaborate with IGS and IVS in the forthcoming reprocessing campaign.
- Participate actively in IAG, AGU and EGU conferences and organize sessions
- Organize working group meetings, splinter group meetings at the said symposia

Members

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Sharyl Byram (USA)
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Gunnar Elgered (Sweden)
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JSG 1 (JSG T.27): Coupling processes between magnetosphere, thermosphere and ionosphere

(Led by ICCT; joint with GGOS, Focus Area on Geodetic Space Weather Research and Commission 4, Sub-Commission 4.3)

Chair: Andres *Calabia Aibar* (China)

Introduction

Consequences of upper-atmosphere conditions on human activity underscore the necessity to better understand and predict effects of the magnetosphere-ionosphere-thermosphere (MIT) processes and of their coupling. This will prevent from their potential detrimental effects on orbiting, aerial and ground-based technologies. For instance, major concerns include the perturbation of electromagnetic signals passing through the ionosphere for an accurate and secure use of global navigation satellite systems (GNSS), and the lack of accurate aerodynamic-drag models required for accurate tracking, decay and re-entry calculations of low Earth orbiters (LEO), including manned and unmanned artificial satellites. In addition, ground power grids and electronics of satellites could be influenced, e.g., by the magnetic field generated by sudden changes in the current system due to solar storms.

Monitoring and predicting Earth's upper atmosphere processes driven by solar activity are highly relevant to science, industry and defense. These communities emphasize the need to increment the research efforts for better understanding of the MIT responses to highly variable solar conditions, as well as detrimental space weather effects on our life and society. On one hand, electron-density variations produce perturbations in speed and direction of various electromagnetic signals propagated through the ionosphere, and reflect as a time-delay in the arrival of the modulated components from which pseudo-range measurements of GNSS are made, and an advance in the phase of signal's carrier waves which affects also carrier-phase measurements. On the other hand, an aerodynamic drag associated with neutral-density fluctuations resulting from upper atmospheric expansion/contraction in response to variable solar and geomagnetic activity increases drag and decelerates LEOs, dwindling the lifespan of space-assets, and making their tracking difficult.

Through interrelations, dependencies and coupling patterns between ionosphere, thermosphere and magnetosphere variability, this JSG aims to improve the understanding of coupled processes in the MIT system, and considerations of the solar contribution. In addition, tides from the lower atmosphere forcing can feed into the electrodynamics; they have a composition effect leading to changes in the MIT system. In this scheme, our tasks are addressed to exploit the knowledge of the tight MIT coupling by investigating multiple types of magnetosphere, ionosphere and thermosphere observations. The final outcome will help to enhance the predictive capability of empirical and physics-based models through interrelations, dependencies and coupled patterns of variability between essential geodetic variables.

Objectives

- Characterize and parameterize the global modes of MIT variations associated with diurnal, seasonal, and space weather drivers, as well as the lower atmosphere forcing.
- Determine and parameterize the mechanisms responsible for discrepancies between observables and the present models.
- Detect and investigate coupled processes in the MIT system for the deciphering of physical laws and principles such as continuity, energy and momentum equations and solving partial differential equations.

Program of activities

- Presenting research findings at major international geodetic or geophysical conferences, meet-ings, and workshops.
- Interacting with related IAG Commissions and GGOS.
- Monitoring research activities of the JSG members and of other scientists, whose research interests are related to the scopes of SG
- Organizing a session at the Hotine-Marussi Symposium 2022.
- Organizing working meetings at international symposia and presentation of research results at appropriate sessions.

Members

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JWG 1: Electron density modelling

(Led by GGOS; joint with Commission 4, Sub-Commission 4.3)

Chair: *Fabricio dos Santos Prol* (Germany)
Vice-Chair: *Alberto Garcia-Rigo* (Spain)

Terms of Reference (ToR)/Description

The main goal of this group is to disseminate and evaluate established methods of 3D electron density estimation in terms of electron density, peak height, Total Electron Content (TEC), or other derived products that can be effectively used for GNSS positioning or for analyzing perturbed conditions due to representative space weather events. It is planned to generate products, showing the general error given by such 3D electron density estimations and, also, distribute information regarding to space weather conditions. To achieve this main goal, the following objectives are defined.

Objectives

- Develop a database, where the methods from the group members will be able to be evaluated in terms of GNSS, radio-occultation, DORIS, in-situ data, altimeters, among other electron density and TEC measurements.
- Evaluate established methods for 3D electron density estimation in order to define their accuracy related to specific parameters of great importance for Space Weather and Geodesy.
- Generate products indicating the space weather conditions and expected errors of the methods.
- Carry out surveys in order to detect if the products are linked to the user's specific needs. Based on an analysis of the user needs, re-adaptations will be identified in order to improve the products in an iterative process. It is planned to define which parameters are of interest for the users and to detect additional information that may be required.

Members

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JWG 2: Improvement of thermosphere models

(Led by GGOS; joint with IAG Commission 4, Sub-Commission 4.3 and ICCC)

Chair: *Christian Siemes* (The Netherlands)
Vice-Chair: *Kristin Vielberg* (Germany)

Terms of Reference (ToR) / Description

Mass density, temperature, composition and winds are important state parameters of the thermosphere that affect drag and lift forces on satellites. Since these significantly influence the orbits of space objects flying at altitudes below 700 km, accurate knowledge of the state of the thermosphere is important for applications such as orbit prediction, collision avoidance, evolution of space debris, and mission lifetime predictions. Drag and lift forces can be inferred from space geodetic observations of accelerometers, which complement other positioning techniques such as GNSS, satellite laser ranging or radar tracking of space objects. The objective of the working group is to improve thermosphere models through providing relevant space geodetic observations and increasing consistency between datasets by advancing processing methods. Broadening the observational data basis with geodetic space observations, which are available now for a time span of 20 years, will also benefit climatological studies of the thermosphere.

Objectives

- Review space geodetic observations and state-of-the-art processing methods
- Advance processing methods to increase consistency between observational datasets
- Improve thermosphere models through providing accurate and consistent space geodetic observations
- Study the impact of improved observational datasets and advanced processing methods on orbit determination and prediction
- Use of improved thermosphere models and observational data sets to forward the investigation of thermosphere variations in the context of climate change

Members

Michael Schmidt (Germany)
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Mona Kosary (Iran)
Lea Zeitler (Germany)
Christopher Mccullough (USA)
Sandro Kraus (Austria)
Saniya Behzadpour (Austria)
Aleš Bezděk (Czech Republic)

JWG 3: Improved understanding of space weather events and their monitoring by satellite missions

(Joint with IAG Commission 4, Sub-Commission 4.3)

Chair: *Alberto Garcia-Rigo* (Spain)
Vice-Chair: *Benedikt Soja* (Switzerland)

Terms of Reference (ToR) / Description

Space weather events cause ionospheric disturbances that can be detected and monitored thanks to estimates of the vertical total electron content (VTEC) and the electron density (Ne) of the ionosphere. Various space geodetic observation techniques, in particular GNSS, satellite altimetry, DORIS, radio occultations (RO) and VLBI are capable of determining such ionospheric key parameters. For the monitoring of space weather events, low latency data availability is of great importance, ideally real time, to enable triggering alerts. At present, however, only GNSS is suited for this task. The use of the other techniques is still limited due latencies of hours (altimetry) or even days (RO, DORIS, VLBI).

The JWG 3 will investigate different approaches to monitor space weather events using the data from different space geodetic techniques and, in particular, combinations thereof. Simulations will be beneficial to identify the contribution of different techniques and prepare for the analysis of real data. Different strategies for the combination of data will be investigated.

Furthermore, the geodetic measurements of the ionospheric parameters will be complemented by direct observations of the solar corona, where solar storms originate, as well as of the interplanetary medium. Spacecrafts like SOHO or ACE have monitored the solar corona and the solar wind for decades and will be beneficial, together with data from other spacecrafts like SDO, in assessing the performance of geodetic observations of space weather events. Data from Parker Solar Probe, which will allow even greater insights, has just recently been made publicly available. Geodetic VLBI is also capable of measuring the electron density of the solar corona when observing targets angularly close to the Sun and will be useful for comparisons.

Other solar-related satellite missions such as Stereo, DSCOVR, GOES, etc. provide valuable information such as solar radiation, particle precipitation and magnetic field variations. Other indications for solar activity - such as the F10.7 index on solar radio flux, SOLERA as EUV proxy or rate of Global Electron Content (dGEC), will also be investigated. The combination and joint evaluation of these data sets with the measurements of space geodetic observation techniques is still a great challenge. Through these investigations, we will gain a better understanding of space weather events and their effect on Earth's atmosphere and near-Earth environment.

Objectives

- Selection of a set of historical representative space weather events to be analysed.
- Determination of key parameters and products affected by the selected space weather events.
- Identification of the main parameters to improve real time determination and the prediction of ionospheric/plasmaspheric VTEC and Ne estimates as well as ionospheric perturbations in case of extreme solar weather conditions.
- Improving the (near) real time determination of the electron density within the ionosphere and plasmasphere to detect space weather events.
- Combination of measurements and estimates derived from space geodetic observation techniques by conducting extensive simulations, combining different data sets and testing different algorithms.
- Comparison and validation using external data, in particular data from spacecraft dedicated to monitoring the solar corona.
- Interpretation of the results. Correlate acquired data/products with space weather events' impact on geodetic applications (e.g. GNSS positioning, EGNOS performance degradation).

Members

Anna Belehaki (Greece)
Anthony J Mannucci (USA)
Jens Berdermann (Germany)
Xiaoqing Pi (USA)
Enric Monte (Barcelona)
Denise Dettmering (Germany)
Consuelo Cid (Spain)
Rami Qahwaji (UK)
Jinsil Lee (Republic of Korea)
Benedikt Soja (Switzerland)
Alberto Garcia-Rigo (Barcelona)

SC 4.4: GNSS Integrity and Quality Control

Chair: *Pawel Wielgosz* (Poland)
Vice-Chair: *Jianghui Geng* (China)
Secretary: *Grzegorz Krzan* (Poland)

Terms of Reference

GNSS constellation is rapidly developing by growing the number of satellites and available signals and frequencies. In addition to two already operational GPS and GLONASS systems, the new Galileo and BDS systems achieved initial operational capabilities. Both GPS and GLONASS are currently undergoing a significant modernization, which adds more capacity, more signals, better accuracy and interoperability, etc. In addition, a rapid development in the mass-market GNSS chipsets has to be also acknowledged.

These new developments in GNSS provide opportunities to create new high-precision GNSS technologies and applications and also to open new research areas. This, however, results in new challenges in multi-GNSS data processing, which primarily concern the positioning integrity and reliability. Recognizing the central role of GNSS in providing high accuracy positioning information, SC4.4 will foster research activities that address integrity, quality control and relevant applications of GNSS in case of multi-constellation and multi-frequency environment. SC4.4 will coordinate activities to deliver practical and theoretical solutions for engineering and scientific applications. Among those applications there are structural and ground deformation monitoring, precise navigation, GNSS remote sensing, geodynamics, etc.

SC4.4 will also encourage strong collaboration with the IAG Services (primarily IGS) as well as with relevant entities within scientific and professional sister organizations (FIG, IEEE and ION).

Objectives

The major objective of SC4.4 is to promote collective research on GNSS Integrity and Quality Control methods and their novel applications to facilitate timely dissemination of scientific findings, to stimulate strong collaborations among researchers and international organizations and the industry.

Program of Activities

- to identify and investigate important scientific and technical issues in GNSS integrity and quality control methods and their applications,
- to stimulate strong collaborations among researchers,
- to organize international conferences and workshops,
- to promote the use reliable GNSS techniques and products in interdisciplinary scientific research and engineering applications.

Working and Study Groups of Sub-Commission 4.4

WG 4.4.1: Quality Control and Integrity Monitoring of Precise Positioning

Chair: *Ahmed El-Mowafy* (Australia)
Vice-Chair: *Christian Tiberius* (The Netherlands)

Description

Global Navigation Satellite Systems (GNSS) are the prime source of precise position information for a variety of applications including intelligent transport systems, autonomous driving, precision agriculture, and deformation monitoring. For such applications, even small errors can incur serious consequences like loss of human lives, liability, and damage to infrastructure, as the provided position information needs to be of high level of reliability.

Any positioning platform, either based on standalone- or augmented-GNSS, is subject to a series of vulnerabilities, e.g. signal faults, interference and carrier phase cycle-slips, which can dramatically deteriorate the reliability of the position solutions. As such, it is crucial to have proper 'Quality Control' mechanisms in place for timely detection of hazardous faults. In addition, monitoring the integrity of the system is an essential part of this quality control procedure, to ensure that the resulting positioning errors are bounded by protection levels that are determined according to the allowable risk probability.

The constituent components of a quality control and integrity monitoring procedure will vary depending on the positioning sensors in use, the positioning method, and the performance requirements. This will in turn raise the need for a thorough research into factors contributing to the quality of a positioning platform as well as their interactions, so as to enable the development of optimal application-dependent quality control and integrity monitoring procedures.

Objectives

- The main objectives of this working group are:
- to derive optimal statistical testing regimes that are capable of detection and exclusion of multiple alternative fault hypotheses using the underlying positioning models,
- to characterize the link between the statistical testing and parameter estimation exercised in data processing so as to develop rigorous quality control frameworks for evaluating the reliability of the position solutions,
- to develop integrity monitoring algorithms for precise positioning methods such as RTK and PPP.
- to disseminate the developed algorithms and numerical results through journal papers and conference proceedings.

Members

Ahmed El-Mowafy (Australia)
Christian Tiberius (The Netherlands)
Chris Rizos (Australia)
Mathieu Jöerger (USA)
Juan Blanch (USA)
Krzysztof Nowel (Poland)
Amir Khodabandeh (Australia)
Nobuaki Kubo (Japan)
Kan Wang (Australia)
Yang Gao (Canada)
Safoora Zaminpardaz (Australia)
Markus Rippl (Germany)

WG 4.4.2: Geophysical Applications of High-Rate GNSS

Chair: *Brendan Crowell* (USA)

Description

The proliferation of high-rate Global Navigation Satellite System (GNSS) data has enabled advances in geophysical monitoring well beyond the original intent of such systems. It has been well demonstrated that models of large and rapid deformation events, such as earthquakes and volcanic eruptions, are improved considerably by including high-rate GNSS observations because of the ability to directly track ground motions from strong shaking out to the permanent offsets. Likewise, the models of the impacts of these events (i.e. ground motions, tsunami predictions) are improved for applications such as early warning and rapid response. In addition to direct measurements of the deformation field, high-rate GNSS can offer additional applications in weather forecasting, space weather through ionospheric tracking, and environmental probing with GNSS reflectometry. High-rate GNSS observations can also be applied to engineering seismology problems such as long-period peak ground motions and can help determine the post-event resiliency of engineered structures. The use of this data for geophysical operations is still in its infancy, and robust algorithms, especially for the quality control and reliability assessment of high-rate GNSS, are required to be developed to ensure future use.

Objectives

The primary objectives for this working group are:

- Objectively characterize the limitations of high-rate GNSS data and determine avenues for improvement,
- Determine the roadblocks to greater adaptation of high-rate GNSS methods,
- Identify stakeholders outside the group that would benefit from high-rate GNSS data, such as monitoring agencies,
- Improve global access to high-rate GNSS data and methodologies.

Members

NA

WG 4.4.3: Reliability of Low-cost & Android GNSS in navigation and geosciences

Chair: *Jacek Paziewski* (Poland)
Vice-Chair: *Robert Odolinski* (New Zealand)

Description

Nowadays, we may observe a rapid development in the mass-market GNSS chipsets including those which are used in smart devices. A real milestone on the way to the introduction of smartphones into location-based applications was the introduction of Android Nougat 7 OS and, therefore making their GNSS raw observations accessible to the general public. This in turn, induced a development of algorithms enhancing the accuracy of positioning with mass-market devices. Hence, now it is feasible to determine the position with low-cost GNSS chipset with a degree of precision which was previously achievable only by survey-grade receivers with advanced processing algorithms.

This working group will endeavor to address and investigate issues related to the usage of low-cost receiver and smartphone GNSS observations to navigation, positioning and selected geoscience applications.

Objectives

The main research will focus on the following objectives:

- To perform a comprehensive characterization of low-cost receiver/smartphone signal quality, including carrier-to-noise density ratio and measurement noise,
- To identify and investigate of the anomalies present in smartphone observables,
- To assess the low-cost receiver/smartphone GNSS positioning performance,
- To develop of novel processing algorithms addressing low-cost receiver/smartphone GNSS observables characteristics,
- To call out new geophysical applications based on GNSS smartphone signals.

Members

Jacek Paziewski (Poland)
Robert Odolinski (New Zeland)
Rafal Sieradzki (Poland)
Martin Hakansson (Sweden)
Amir Khodabandeh (Australia)
Xiaohong Zhang (China)
Eugenio Realini (Italy)
Umberto Robustelli (Italy)
Vassilis Gikas (Greece)
Rene Warnant (Belgium)
Xiaopeng Gong (China)
Augusto Mazzoni (Italy)
Dimitrios Psychas (The Netherlands)
Guangcai Li (China)
Safoora Zaminpardaz (Australia)

JSG 4.4.4: Assessment and validation of IGS products and open-source scientific software (Joint WG between IAG and IGS)

Chair: *Yidong Lou* (China)
Vice-Chair: *Peng Fang* (USA)

Description

High-precision GNSS applications require not only the high-accuracy GNSS products but also the high-precision software. The IGS (International GNSS Service) has been maintaining public available high-quality products for decades, including the GNSS satellite ephemerides, geocentric coordinates of IGS tracking stations, earth rotation, atmospheric parameters and biases, to satisfy the objectives of a wide range of scientific research and applications, which has greatly benefited the GNSS community.

With the modernization of GPS and GLONASS and the in-service of Galileo, Beidou and QZSS, the precision and timelines of IGS products are continuously improved and types are under expansions. On the other hand, however, we seldom have credible open-source high-precision scientific software for enormous users. The open-source of more high-precision/scientific software can significantly boost the utilization of IGS products in the scientific community and promote the popularization of GNSS in high-precision applications.

Although a few software packages have been open sourced recently, they may be far from enough to demonstrate their applicability in high-precision applications, and questions like how the performance of these current open-source software is and what kinds of applications they can satisfy remain unclear. This study group is therefore set up mainly to investigate the performance of different software comprehensively, improve their capability through international coordination, encourage the open-source of more professional software, and bridge the IAG and IGS regarding the applications of IGS products in diverse fields.

Objectives

The main objectives of this working group are:

- to investigate the performance and reliability of different open-source scientific software comprehensively, so as to provide important references to users for choosing the most suitable software in different applications
- to provide a platform to facilitate the communications between the developers and users of the open-source high-precision/scientific software, so as to promote the improvement of algorithms and potential scientific application.
- to collect and disseminate information of open-source high-precision/scientific software for the scientific community,
- to act as a bridge between the IAG and IGS regarding the applications of the high-precision IGS products in diverse fields.

Members

Yidong Lou (China)
Peng Fang (USA)
Weixing Zhang (China)
Jan Dousa (Czech)
Feng Zhou (China)
D. Ibáñez (Spain)
Xiaolei Dai (China)
Yuanqing Pan (China)
Pavel Vaclavovic (Czech Republic)
Fu Zheng (China)
Berkay Bahadur (Turkey)
Haojun Li (China)

WG 4.4.5: Spoofing and Interference of GNSS

Chair: *Lakshay Narula* (USA)
Vice-Chair: *Chengjun Guo* (China)

Description

Global navigation satellite system (GNSS) signals are relatively weak, and thus susceptible to intentional and unintentional radio frequency interference (RFI). GNSS interference can lead to denial-of-service (by intentional or unintentional jamming), or can make the victim deduce a false position fix and/or a false clock offset (by intentional spoofing). Such interference is of serious concern for civil aviation, freight transportation, financial trading, military operations, etc. The last few years have seen a dramatic rise in GNSS RFI activity across the world, with verified reports of GPS spoofing in Ukraine/Black Sea, Syria, Shanghai, and some other parts of China.

As low-cost GNSS jammers continue to be an issue, the GNSS spectrum is facing a renewed threat from terrestrial communications in neighboring frequency bands. With low-cost software-defined radios, a GNSS spoofer can now be downloaded from the internet. As safety-of-life applications like self-driving cars and air taxis look for reliable and secure positioning and navigation techniques, GNSS spoofing and interference issues are becoming an important concern for the GNSS research community.

Current GNSS RFI countermeasures range from encryption of signals to interference detection via sensor fusion, and from use of directional antennas to monitoring of ADC gain. This working group will bring together experts in the field of GNSS spoofing and interference to consolidate the current body of knowledge on the topic, identify promising future directions, and to debate on the efficacy of the current and proposed countermeasures to GNSS RFI.

Objectives

The primary objectives of this working group are to examine and identify promising future directions on the following topics:

- GNSS resilience against jamming, including jamming from terrestrial communication networks (e.g. Ligado) and on-chip communication (e.g., USB3).
- Sensor fusion for GNSS spoofing detection.
- Current proposals for navigation message and/or spreading code authentication and encryption for non-military use, e.g., Galileo High Accuracy Service.

- The role of upcoming massive low earth orbit (LEO) satellite constellations in resilience to GNSS jamming and spoofing.
- Attacks and defenses for secure clock synchronization.
- Global GNSS RFI monitoring and situational awareness via dedicated and/or opportunistic probes.

In addition, this working group will encourage GNSS interference wardriving to collect data evidence of interesting and credible GNSS RFI activity in different parts of the world.

Members

NA

Inter-Commission Committee on Theory (ICCT)

President: **Pavel Novák** (Czech Republic)
Vice President: **Mattia Crespi** (Italy)

http://icct.iag-aig.org

Terms of Reference

The Inter-Commission Committee on Theory (ICCT) was formally approved and established after the IUGG XXI Assembly in Sapporo, 2003, to succeed the former IAG Section IV on General Theory and Methodology and, more importantly, to interact actively and directly with other IAG entities, namely commissions, services and the Global Geodetic Observing System (GGOS). In accordance with the IAG by-laws, the first two 4-year periods were reviewed in 2011. IAG approved the continuation of ICCT at the IUGG XXIII Assembly in Melbourne, 2011. At the IUGG XXIV Assembly in Prague, 2015, ICCT became a permanent entity within the IAG structure.

Recognizing that observing systems in all branches of geodesy have advanced to such an extent that geodetic measurements

(i) are now of unprecedented accuracy and quality, can readily cover a region of any scale up to tens of thousands of kilometres, yield non-conventional data types, and can be provided continuously;
and consequently,

(ii) demand advanced mathematical modelling in order to obtain the maximum benefit of such technological advance, ICCT
  (1) strongly encourages frontier mathematical and physical research, directly motivated by geodetic need and practice, as a contribution to science and engineering in general and theoretical foundations of geodesy in particular;
  (2) provides the channel of communication amongst different IAG entities of commissions, services and projects on the ground of theory and methodology, and directly cooperates with and supports these entities in the topical work;
  (3) helps IAG in articulating mathematical and physical challenges of geodesy as a subject of science and in attracting young talents to geodesy. ICCT strives to attract and serve as home to all mathematically motivated and oriented geodesists as well as to applied mathematicians; and
  (4) encourages closer research ties with and gets directly involved in relevant areas of Earth sciences, bearing in mind that geodesy has always been playing an important role in understanding the physics of the Earth.

Objectives

The overall objectives of the ICCT are:

- to act as international focus of theoretical geodesy,
- to encourage and initiate activities to advance geodetic theory in all branches of geodesy,
- to monitor developments in geodetic methodology.

To achieve the objectives, the ICCT interacts and collaborates with the IAG Commissions, GGOS and other IAG related entities (services, projects).

Structure

The structure of Inter-Commission Committees is specified in the IAG by-laws. The ICCT Steering Committee consists of the President, Vice-President, Past-President, representatives from each of the IAG Commissions, GGOS and of two members-at-large.

ICCT activities are undertaken by study groups. By the inter-commission nature of ICCT, these study groups are joint study groups, affiliated to one or more of the Commissions and/or to GGOS.

Program of Activities

The ICCT's program of activities include:

- participation as (co-)conveners of geodesy sessions at major conferences such as IAG, EGU and AGU,
- organization of Hotine-Marussi symposia,
- initiation of summer schools on theoretical geodesy,
- and maintaining a website for dissemination of ICCT related information.

Steering Committee

President	*Pavel Novák* (Czech Rep.)
Vice-President	*Mattia Crespi* (Italy)
Past-President	*Nico Sneeuw* (Germany)
Representatives of IAG entities:	
Commission 1	*Christopher Kotsakis* (Greece)
Commission 2	*Mirko Reguzzoni* (Italy)
Commission 3	*Janusz Bogusz* (Poland)
Commission 4	*Allison Kealy* (Australia)
GGOS	*Michael Schmidt* (Germany)
IGFS	*Riccardo Barzaghi* (Italy)
IERS	*Jürgen Müller* (Germany)
Members at large:	
IAG	*Bofeng Li* (China)
IAG	*Marcelo Santos* (Canada)

Joint Study Groups

The following list names ICCT joint study groups (JSG) for the 2019-2023 period. Their chairs are indicated in boldface. The numbers behind the names denote the affiliation of JSG to the IAG Commissions or GGOS.

JSG T.23	Spherical and spheroidal integral formulas of the potential theory for transforming classical and new gravitational observables *M. Šprlák* (Czech Rep.) 2, GGOS
JSG T.24	Integration and co-location of space geodetic observations and parameters *K. Sośnica* (Poland) 1, 2, 3, 4, GGOS
JSG T.25	Combining geodetic and geophysical information for probing Earth's inner structure and its dynamics *R. Tenzer* (Hong Kong) 2, 3, GGOS
JSG T.26	Geoid/quasi-geoid modelling for realization of the geopotential height datum *J. Huang* (Canada) 2, GGOS
JSG T.27	Coupling processes between magnetosphere, thermosphere and ionosphere *A. Calabia* (China) 4, GGOS
JSG T.28	Forward gravity field modelling of known mass distributions *D. Tsoulis* (Greece) 2, 3, GGOS
JSG T.29	Machine learning in geodesy *B. Soja* (Switzerland) 2, 3, 4
JSG T.30	Dynamic modeling of deformation, rotation and gravity field variations *Y. Tanaka* (Japan) 2, 3, GGOS
JSG T.31	Multi-GNSS theory and algorithms *A. Khodabandeh* (Australia) 1, 4, GGOS
JSG T.32	High-rate GNSS for geoscience and mobility *M. Crespi* (Italy) 1, 3, 4, GGOS
JSG T.33	Time series analysis in geodesy and geodynamics *W. Kosek* (Poland) 1, 3, 4, GGOS
JSG T.34	High resolution harmonic analysis and synthesis of potential fields *S. Claessens* (Australia) 2, GGOS
JSG T.35	Advanced numerical methods in physical geodesy *R. Čunderlík* (Slovakia) 2, GGOS
JSG T.36	Dense troposphere and ionosphere sounding *G. Savastano* (Luxembourg) 4, GGOS
JSG T.37	Theory and methods related to combination of high-resolution topographic/bathymetric models in geodesy *D. Carrion* (Italy) 2, GGOS

JSG T.23: Spherical and spheroidal integral formulas of the potential theory for transforming classical and new gravitational observables

Chair: *M. Šprlák* (Czech Republic)
Affiliation: Commission 2 and GGOS

Introduction

The gravitational field represents one of the principal properties of any planetary body. Physical quantities, e.g., the gravitational potential or its gradients (components of gravitational tensors), describe gravitational effects of any mass body. They help indirectly in sensing inner structures of planets and their (sub-)surface processes. Thus, they represent an indispensable tool for understanding inner structures and processes of planetary bodies and for solving challenging problems in geodesy, geophysics and other planetary sciences.

Various measurement principles have been developed for collecting gravitational data by terrestrial, marine, airborne or satellite sensors. From a theoretical point of view, different parameterizations of the gravitational field have been introduced. To transform observable parameters into sought parameters, various methods have been introduced, e.g., boundary-value problems of the potential theory have been formulated and solved analytically by integral transformations.

Transforms based on solving integral equations of Stokes, Vening-Meinesz and Hotine have traditionally been of significant interest in geodesy as they accommodated gravity field observables in the past. However, new gravitational data have recently become available with the advent of satellite-to-satellite tracking, Doppler tracking, satellite altimetry, satellite gravimetry, satellite gradiometry and chronometry. Moreover, gravitational curvatures have already been measured in laboratory. New observation techniques have stimulated formulations of new boundary-value problems, equally as possible considerations on a tie to partial differential equations of the second order on a two-dimensional manifold. Consequently, the family of surface integral formulas has considerably extended, covering now mutual transformations of gravitational gradients of up to the third order.

In light of numerous efforts in extending the apparatus of integral transforms, many theoretical and numerical issues still remain open. Within this JSG, open theoretical questions related to existing surface integral formulas, such as stochastic modelling, spectral combining of various gradients and assessing numerical accuracy, will be addressed. We also focus on extending the apparatus of spheroidal integral transforms which is particularly important for modelling gravitational fields of oblate or prolate planetary bodies.

Objectives

This JSG plans to:

- Study noise propagation through spherical and spheroidal integral transforms.
- Propose efficient numerical algorithms for precise evaluation of spherical and spheroidal integral transformations.
- Develop mathematical expressions for calculating the distant-zone effects for spherical and spheroidal integral transformations.
- Study mathematical properties of differential operators in spheroidal coordinates which relate various functionals of the gravitational potential.
- Formulate and solve spheroidal gradiometric and spheroidal curvature boundary-value problems.
- Complete the family of spheroidal integral transforms among various types of gravitational gradients and to derive corresponding integral kernel functions.
- Investigate optimal combination techniques of various gravitational gradients for gravitational field modelling at all scales.

Program of Activities

- Presenting findings at international geodetic or geophysical conferences, meetings and workshops.
- Interacting with IAG Commissions and GGOS.
- Monitoring research activities of JSG members and other scientists whose research interests are related to scopes of this JSG.
- Organizing a session at the Hotine-Marussi Symposium 2022.
- Providing a bibliographic list of publications from different branches of the science relevance to scopes of this JSG.

Membership

Michal Šprlák (Czech Republic), chair
Sten Claessens (Australia)
Mehdi Eshagh (Sweden)
Ismael Foroughi (Canada)
Peter Holota (Czech Republic)
Juraj Janák (Slovakia)
Otakar Nesvadba (Czech Republic)
Pavel Novák (Czech Republic)
Vegard Ophaug (Norway)
Martin Pitoňák (Czech Republic)
Michael Sheng (Canada)
Natthachet Tangdamrongsub (USA)
Robert Tenzer (Hong Kong)

JSG T.24: Integration and co-location of space geodetic observations and parameters

Chair: *K. Sośnica* (Poland)
Affiliation: Commissions 1, 2, 3 and 4, GGOS

Introduction

Many geodetic parameters can be retrieved using various techniques of space geodesy. For instance, all satellite techniques are sensitive to a geocenter motion and gravity field variations. However, some techniques are affected more by systematic observation errors than other techniques. Earth's rotation parameters from sub-daily to daily temporal scales can be determined using all techniques of space geodesy with higher or lower accuracy, and with better or worse temporal resolutions. Precise orbits of satellites may be based on a single technique or multiple techniques that shall mitigate system-specific orbital systematic errors.

Recently, a series of satellite missions co-locating different space geodetic techniques has been launched:

- SLR and GNSS: Galileo (all satellites), GLONASS (all satellites), QZSS (all satellites), IRNSS (all satellites), GPS (2 satellites), BeiDou/COMPASS (selected satellites), CHAMP, GRACE-A/B, GOCE, SWARM-A/B/C, ICESat-2, COSMIC-2, Terra-SAR, TanDEM-X, GRACE Follow-On A/B, etc.
- DORIS and SLR: TOPEX/Poseidon, ENVISAT, CRYOSAT-2, SARAL and Jason-1 (after 2009),
- VLBI and SLR: RadioAstron,
- VLBI, SLR, and GNSS: APOD,
- DORIS, GNSS and SLR: Jason-2/3, HY-2A and Sentinel-3A/B,
- SLR, VLBI, GNSS and DORIS: GRASP and E-GRASP (planned missions).

SLR retroreflectors are passive and relatively cheap devices; thus, they are installed on-board many low- and high-orbiting satellites. Many low-orbiting satellites for ocean monitoring are equipped with DORIS and GNSS receivers for precise orbit determination, and with SLR retroreflectors for the orbit validation. DORIS receivers are installed on many satellites which require precise ephemeris and orbit below 2000 km. Missions dedicated to Earth's gravity field recovery are typically equipped with GNSS receivers and SLR retroreflectors. Most of the GNSS satellites are equipped with SLR retroreflectors (except for GPS). VLBI telescopes are typically slow as they are dedicated to tracking extra-galactic quasars. Hence, many VLBI telescopes have problems with tracing fast-moving low-orbiting targets that are planned for co-location on-board satellites. However, first experiments using the APOD satellite with a VLBI transmitter and SLR retroreflector was successfully performed in Australia. Unfortunately, the APOD GPS receiver failed soon after the satellite launch which caused some issues with the accuracy of the determined orbit when the number of SLR observations was insufficient.

Despite many LEO satellites equipped with two or three techniques of space geodesy, the full potential of the co-location on-board LEO has not yet been entirely explored in terms of deriving combined geodetic parameters. SLR observations to LEO are typically used only for validation of GPS-based or DORIS-based orbits. SLR observations to LEO and GNSS do not contribute at all to realization of the International Terrestrial Reference System despite GNSS and LEO satellites contributing to GNSS and DORIS solutions, respectively.

Recently, the International Laser Ranging Service initiated a series of special tracking campaigns dedicated to tracking new LEO and GNSS spacecraft which increased the amount of collected data with a perspective of their full co-location in space. The combination of solutions based on GNSS, SLR, LLR, DORIS and VLBI requires a profound investigation of biases and systematic effects affecting all individual techniques. Neglecting systematic effects may lead to degradation of solutions and to absorption of various systematic effects by global geodetic parameters.

The main goal of this JSG is to investigate methods to combine global geodetic parameters derived from multiple techniques of space geodesy with the major focus on those missions capable of co-locating and integrating different observation techniques. We aim at improving quality and reliability of global geodetic parameters and realization of the terrestrial reference system through integration of different microwave techniques with laser techniques. We will also explore benefits emerging from co-locating geodetic techniques on-board low and high-orbiting satellites. We aim at detailed analyses related to system-specific issues and systematic effects emerging from combining different techniques of space geodesy, and at the assessment of their contributions to combined global geodetic parameters.

Objectives

- Determination of global geodetic parameters using combined space geodetic observations.
- Determination of geocenter motion from: SLR observations to passive and active satellites, DORIS, Galileo, GPS, GLONASS, and BeiDou or possibly also VLBI (using inverse methods).
- Separation of geophysical signals in the geocenter motion from the technique-specific and system-specific errors, employing the co-location in space between SLR and GNSS using Galileo, BeiDou, and GLONASS satellites for deriving common parameters.
- Analysis of potential usability of SLR observations to active LEO satellites together with GNSS and DORIS data for deriving global geodetic parameters.
- Analysis of daily pole coordinates and of length-of-day variations using combined SLR and microwave observations to different GNSS and LEO satellites with DORIS receivers, and the comparison with respect to LLR and VLBI results.
- Determination of sub-daily Earth's rotation parameters from VLBI, GPS, GLONASS, Galileo and SLR observations to LEO and geodetic satellites.
- Precise orbit determination of LEO and GNSS satellites using combined SLR and microwave observations – GNSS and DORIS.
- Estimation of geodetic parameters using GNSS employing time-variable gravity field models derived from SLR, active LEOs and GRACE. Assessment of the vulnerability of satellite orbits to low-degree Earth's gravity field depending on the satellite heights.
- Homogenization of tropospheric delay models for co-located space geodetic stations. Separation of the wet and hydrostatic tropospheric delay; analysis of the

horizontal gradients for optical and microwave techniques.
- Combination of SLR observations to various LEO missions: Sentinel-3A/3B, GRACE, GRACE-FO, GOCE, SWARM-A/B/C, Jason-2/3 to realize the terrestrial reference frames.
- Determination of time-variable low-degree gravity field using SLR observation to passive geodetic satellites and GNSS-based orbits of LEO satellites to fill a gap between GRACE and GRACE-FO missions,
- Estimation of Earth's rotation parameters by combining LLR, SLR and GNSS, and their comparison with VLBI results.

Program of activities

- To launch a questionnaire for the current integration of techniques and finalized co-location in space experiments.
- To open a web page with information concerning the co-location in space, the combination of global geodetic parameters and the exchange of ideas, provision and updating the bibliographic list of references of research results and relevant publications from different combination centers.
- To launch a proposal for two state-of-the-art review papers on co-location on-board LEO and GNSS and combination of global geodetic parameters co-authored by JSG members.
- To organize a session at the Hotine-Marussi Symposium 2022.
- To promote sessions and presentation of the research results at international symposia both related to Earth science, e.g., IAG/IUGG, EGU, AGU, EUREF, IGS and ILRS.

Membership

Krzysztof Sośnica (Poland), chair
Mathis Blossfeld (Germany)
Janina Boisits (Austria)
Grzegorz Bury (Poland)
Florian Dilssner (Germany)
Susanne Glaser (Germany)
Toshimichi Otsubo (Japan)
Erik Schnoemann (Germany)
Dariusz Strugarek (Poland)
Daniela Thaller (Germany)
Tzu-Pang Tseng (Australia)
Radosław Zajdel (Poland)
Julian Zeitlhöfler (Germany)

JSG T.25: Combining geodetic and geophysical information for probing Earth's inner structure and its dynamics

Chair: *R. Tenzer* (Hong Kong)
Affiliation: Commissions 2 and 3, GGOS

Introduction

The seismic tomography is primarily used to provide images of the Earth's inner structure based on the analysis of seismic waves due to earthquakes and (controlled) explosions. This technique involves several different methods for processing P-, S- and surface waves on the principle of solving inverse problems for finding locations of reflection and refraction of wave pathways in order to create topographic models. In this way, 3D models of P- and S-wave seismic velocity anomalies are obtained which can be interpreted as structural, thermal or compositional variations inside the Earth. Focusing on the Earth's density structure, the conversion between seismic velocities and mass densities are adopted to construct regional or global seismic density models of the crust and the mantle. Two major limiting aspects restrict possibilities of recovering Earth's density structure realistically. The first one is practical. Since active seismic experiments are relatively expensive, large parts of the world are not yet covered sufficiently by seismic surveys, most remarkably most of world's oceans as well as remote parts of Antarctica, Greenland, Africa and South America. The other aspect is of a theoretical nature. The determination of mass density from seismic data could be ambiguous while affected by many uncertainties, meaning that the relationship between seismic velocities and mass densities is not unique. Actually, the density structure inside the Earth is controlled by many factors such a thermal state or mineral composition.

Gravity data has been used to interpolate the information about the Earth's density structure (or density interfaces) where seismic data coverage is uneven or sparse. The National Geospatial-Intelligence Agency in conjunction with its partners from around the world has begun to develop a new global gravitational model, EGM2020, which should be released publically in 2020. EGM2020 should significantly improve the accuracy (as well as the actual resolution) of the global Earth's gravity field. This will be achieved by incorporating new data sources and procedures. Updated satellite gravity information from the GOCE and GRACE missions will better support the lower harmonics, globally. Multiple new acquisitions (terrestrial, airborne and shipborne) of gravimetric data over specific regions, will provide improved global coverage and resolution over the land as well as for coastal and some oceanic areas. Ongoing accumulation of satellite altimetry data will contribute to refinement and accuracy improvement of the marine gravity field, most notably in polar and near-coastal regions. A significant improvement is also anticipated over large remote regions in Africa, South America, Greenland and Antarctica. EGM2020 will provide opportunities to improve the current knowledge about the Earth's inner structure and processes particularly in regions with a low seismic data coverage. Gravimetric interpretation of the Earth's inner density structure is, however, a non-unique problem because infinity many density configurations could be attributed just to the one gravity field solution. Moreover, the gravity inversion is (in a broader mathematical context) an ill-posed problem.

To overcome partially theoretical deficiencies and practical restrictions of both, seismic and gravimetric methods for the recovery of the Earth's inner density structure, techniques for a combined or constrained inversions of gravity and seismic data are optimally applied, while incorporating additional geophysical, geological and geodynamic constraints. Many such methods already exist or could be developed and further improved within the framework of scientific activities of members of this (multidisciplinary) study group over the next four years. This is achievable, given their expertise in the field of geodesy, geophysics, mathematics and to some extent also geology.

We expect that our research activities will substantially contribute to the current knowledge of the lithospheric structure, focusing on continental regions of Africa and South America and other continents where seismic data are sparse. Our ongoing research already involves Antarctica and central part of Eurasia. Moreover, a special attention will be given to study the lithospheric structure beneath the Indian Ocean, which is probably the most complex, but the least understood. Despite the lithosphere is the most heterogeneous layer inside the Earth, large lateral structural irregularities are still present even deeper within the mantle below the lithosphere-asthenosphere boundary that are mainly attributed to the mantle convection pattern. The combined gravity and seismic data will be exploited in order to improve existing global or continental-scale mantle density models. A further improvement of the knowledge on the Earth's inner structure is important, among many other subjects, also for a better understanding of the response of the lithosphere to the mantle convection. This involves numerous study topic, including but not limited to the compensation stage of the crust/lithosphere, the lithospheric strength, mechanisms behind the oceanic subduction, the relation between the mantle convection pattern and the global tectonic configuration (and its spatio-temporal variations), the glacial isostatic adjustment, volcanic processes, or geo-hazard. The members of this study group will address some of these aspects within the following overall objectives.

Objectives

The main objectives of the JSG are as follows:

- Improvement of (regional and continental-scale) lithospheric density models based on combining geodetic and geophysical data and additional geological constraining information, focusing mainly on regions with insufficient seismic data coverage. Special emphasis will be given to Africa, Greenland and South America. Studies will involve also Indian and Pacific Oceans.
- Development of a preliminary global density model of the mantle bellow the lithosphere-asthenosphere boundary based on the combined analysis of seismic and gravity data, focusing on the seismic data conversion to mass densities within the gravimetric inversion scheme constrained by geothermal, geochemical, geodynamic and other information.
- Contribution to a better understanding of the interaction between the mantle dynamics and the lithospheric state and structure.

Program of Activities

Presenting research findings at major international geodetic or geophysical conferences, meetings and workshops.
Interacting with related IAG Commissions and GGOS.
Monitoring research activities of the JSG members and of other scientists, whose research interests are relevant to the scopes of the JSG.

Organizing a session at the Hotine-Marussi Symposium 2022.

Providing bibliographic list of publications from different branches of science relevant to JSG scopes.

Membership

Robert Tenzer (Hong Kong), chair
Aleksej Baranov (Russia)
Mohammad Bagherbandi (Sweden)
Carla Braitenberg (Italy)
Wenjin Chen (China)
Róbert Čunderlík (Slovakia)
Franck EK Ghomsi (Cameroon)
Mirko Reguzzoni (Italy)
Lars Sjöberg (Sweden)

JSG T.26: Geoid/quasi-geoid modelling for realization of the geopotential height datum

Chair: *J. Huang* (Canada)
Affiliation: Commission 2 and GGOS

Introduction

The geopotential height datum is realized by a gravimetric geoid/quasi-geoid model. The geoid/quasi-geoid model can now be determined with the accuracy of a few centimeters in a number of regions around the world; it has been adopted in some as a height datum to replace spirit-leveling networks, e.g., in Canada and New Zealand. A great challenge is the 1-2 cm accuracy anywhere to be compatible with the accuracy of ellipsoidal heights measured by the GNSS technology. This requires an adequate theory and its numerical realization, to be of the sub-centimeter accuracy, and the availability of commensurate gravity data and digital elevation models (DEMs).

Geoid/quasi-geoid modelling involves the combination of satellite, airborne and surface gravity data through the remove-compute-restore method, employing various modelling techniques such as the Stokes integration, least-squares collocation, spherical radial base functions or spherical harmonics. Satellite gravity data from recent gravity missions (GRACE and GOCE) enable to model the geoid components with the accuracy of 1-2 cm at the spatial resolution of 100 km. Airborne gravity data are covering more regions with a variety of accuracies and spatial resolutions such as the US GRAV-D project. They often overlap with surface gravity data which are still essential in determining the high-resolution geoid model.

In the meantime, DEMs required for the gravity reduction have achieved higher spatial resolutions with a global coverage. In order to understand how accurately the geoid model can be determined, the 1 cm geoid experiment was carried out in a test region in Colorado, USA by more than ten international teams. The state-of-the-art airborne data was provided for this experiment by US NGS. The test results reveal that differences between geoid models by these teams are at the level of 2-4 cm in terms of the standard deviation with a range of decimeters. Reducing these differences is necessary for realization of geopotential height datums and the International Height Reference System (IHRS). This will require a thorough examination and assessment of both methods and data.

Objectives

The scope of this JSG covers all aspects of geoid/quasi-geoid modelling, in particular focuses on:

- Adoption of physical parameters such as *GM*.
- Determination and adoption of W_0.
- Geo-center convention with respect to the International Terrestrial Reference Frame (ITRF).
- Adoption of a Geodetic Reference System.
- Identification of data requirements and gaps.
- Gravity data gridding methods.
- Downward continuation of high-altitude airborne gravity data.
- Spatial and spectral modelling of topographic effects considering mass density variation.
- Combination of satellite, airborne and surface gravity data.
- Separation between the geoid and quasi-geoid.
- Estimation of data and geoid/quasi-geoid model errors.
- External validation data and methods for the geoid/quasi-geoid model.
- Dynamic geoid/quasi-geoid modelling.
- New geodetic boundary-value problems.

Program of Activities

The JSG will achieve its objectives through:

- Involving and supporting new generation of geoid modelers.
- Organizing splinter meetings in coincidence with major IAG conferences and a series of online workshops.
- Circulating and sharing information, ideas, progress reports, papers and presentations.
- Organizing a session at the Hotine-Marussi Symposium 2022.
- Supporting and cooperating with IAG commissions, services, GGOS and other study and working groups on gravity modelling and height system, in particular GGOS IHRS working group, and International Service for the Geoid (ISG).

Membership

Jianliang Huang (Canada), chair
Jonas Ågren (Sweden)
Riccardo Barzaghi (Italy)
Heiner Denker (Germany)
Bihter Erol (Turkey)
Christian Gerlach (Germany)
Christian Hirt (Germany)
Juraj Janák (Slovakia)
Tao Jiang (China)
Robert W. Kingdon (Canada)
Xiaopeng Li (USA)
Urs Marti (Switzerland)
Ana Cristina de Matos (Brazil)
Pavel Novák (Czech Republic)

Laura Sanchez (Germany)
Matej Varga (Croatia)
Marc Véronneau (Canada)
Yanming Wang (USA)
Xinyu Xu (China)

JSG T.27: Coupling processes between magnetosphere, thermosphere and ionosphere

Chair: *A. Calabia* (China)
Affiliation: Commission 4 and GGOS

Introduction

Consequences of upper-atmosphere conditions on human activity underscore the necessity to better understand and predict effects of the magnetosphere-ionosphere-thermosphere (MIT) processes and of their coupling. This will prevent from their potential detrimental effects on orbiting, aerial and ground-based technologies. For instance, major concerns include the perturbation of electromagnetic signals passing through the ionosphere for an accurate and secure use of global navigation satellite systems (GNSS), and the lack of accurate aerodynamic-drag models required for accurate tracking, decay and re-entry calculations of low Earth orbiters (LEO), including manned and unmanned artificial satellites. In addition, ground power grids and electronics of satellites could be influenced, e.g., by the magnetic field generated by sudden changes in the current system due to solar storms.

Monitoring and predicting Earth's upper atmosphere processes driven by solar activity are highly relevant to science, industry and defense. These communities emphasize the need to increment the research efforts for better understanding of the MIT responses to highly variable solar conditions, as well as detrimental space weather effects on our life and society. On one hand, electron-density variations produce perturbations in speed and direction of various electromagnetic signals propagated through the ionosphere, and reflect as a time-delay in the arrival of the modulated components from which pseudo-range measurements of GNSS are made, and an advance in the phase of signal's carrier waves which affects also carrier-phase measurements. On the other hand, an aerodynamic drag associated with neutral-density fluctuations resulting from upper atmospheric expansion/contraction in response to variable solar and geomagnetic activity increases drag and decelerates LEOs, dwindling the lifespan of space-assets, and making their tracking difficult.

Through interrelations, dependencies and coupling patterns between ionosphere, thermosphere and magnetosphere variability, this JSG aims to improve the understanding of coupled processes in the MIT system, and considerations of the solar contribution. In addition, tides from the lower atmosphere forcing can feed into the electrodynamics; they have a composition effect leading to changes in the MIT system. In this scheme, our tasks are addressed to exploit the knowledge of the tight MIT coupling by investigating multiple types of magnetosphere, ionosphere and thermosphere observations. The final outcome will help to enhance the predictive capability of empirical and physics-based models through interrelations, dependencies and coupled patterns of variability between essential geodetic variables.

Objectives

- Characterize and parameterize global modes of MIT variations associated with diurnal, seasonal and space weather drivers as well as the lower atmosphere forcing.
- Determine and parameterize mechanisms responsible for discrepancies between observables and present models.
- Detect and investigate coupled processes in the MIT system for the deciphering of physical laws and principles such as continuity, energy and momentum equations and solving partial differential equations.

Program of Activities

- Presenting research findings at major international geodetic or geophysical conferences, meetings, and workshops.
- Interacting with related IAG Commissions and GGOS.
- Monitoring research activities of the JSG members and of other scientists, whose research interests are related to the scopes of SG
- Organizing a session at the Hotine-Marussi Symposium 2022.
- Organizing working meetings at international symposia and presentation of research results at appropriate sessions.

Membership

Andres Calabia Aibar (China), chair
Emmanuel Abiodun Ariyibi (Nigeria)
Toyese Tunde Ayorinde (Brazil)
Olawale S. Bolaji (Nigeria)
Oluwaseyi Emmanuel Jimoh (Nigeria)
Gang Lu (USA)
Naomi Maruyama (USA)
Astrid Maute (USA)
Piyush M. Metha (USA)
Charles Owolabi (Nigeria)
Liang Yuan (China)

JSG T.28: Forward gravity field modelling of known mass distributions

Chair: *D. Tsoulis* (Greece)
Affiliation: Commissions 2 and 3, GGOS

Introduction

The geometrical definition of the shape and numerical evaluation of the corresponding gravity signal of any given mass distribution express a central theme in gravity field modelling. Involving different theoretical and computational aspects of the potential field theory and including the element of interpreting the computed signal by comparing it with the observed gravity field, the specific research topic determines a characteristic interface between geodesy and geophysics.

Theoretical and methodological aspects of mass modelling concern a wide range of applications, from computing gravity anomalies and geoid to reducing satellite gradiometry data or solving an extended family of integral equations of the potential theory. Directly linked to real mass density distributions in the Earth's interior, the problem of computing the potential function of given mass density distributions and its spatial derivatives up to higher orders defines the core of forward gravity field modelling, while also constituting an integral part of an inverse modelling flowchart in geophysics.

The availability of an abundance of terrestrial and satellite data of global coverage and increasing spatial resolution provides a challenging framework for revisiting known theoretical aspects and especially investigating computational limits and possibilities of forward gravity modelling induced by known mass distributions. Satellite observations provide global grids of gravity related quantities at satellite altitudes, global crustal databases offer detailed layered information of the shape and consistency of the Earth's crust, while satellite methods produce digital elevation models that represent a continental part of the topographic surface with unprecedented resolution.

The current datasets enable the consideration of several theoretical, methodological and computational aspects of forward gravity field modelling. For instance, dense digital elevation models provide a unique input dataset that challenges the evaluation of precise terrain effects, especially in areas of very steep terrain. At the same time and due to the availability of new data, the complete theoretical framework that evaluates the gravity effect of a given distribution using analytical, numerical or spectral techniques emerges again at the forefront of research, examining both ideal bodies and real distributions. Finally, the existence of detailed information of the structure in the Earth's interior provides an opportunity to revisit synthetic Earth reference models by computing the actual gravity effect induced by these distributions and validate it against the observed gravity signal obtained by the available gravity field models.

Objectives

- Examine new theoretical developments (numerical, analytical or spectral) in expressing the gravity signal of ideal geometric distributions.
- Perform validation studies of precise terrain effects over rugged mountainous topography.
- Compute the gravity effect of structures in the Earth's interior and embed this effort in the frame of a synthetic reference Earth model.

Program of Activities

- Participation in forthcoming IAG conferences with splinter meetings and proposed sessions.
- Preparation of joint publications with JSG members.
- Organization of a session at the Hotine-Marussi Symposium 2022.

Membership

Dimitrios Tsoulis (Greece), chair
Carla Braitenberg (Italy)
Christian Gerlach (Germany)
Ropesh Goyal (India)
Olivier Jamet (France)
Michael Kuhn (Australia)
Pavel Novák (Czech Republic)
Konstantinos Patlakis (Greece)
Daniele Sampietro (Italy)
Matej Varga (Croatia)
Jérôme Verdun (France)

JSG T.29: Machine learning in geodesy

Chair: *B. Soja* (Switzerland)
Affiliation: Commissions 2, 3 and 4

Introduction

Due to the exponential increase in computing power over the last decades, machine learning has grown in importance for several applications. In particular, deep learning, i.e., machine learning based on deep neural networks, typically performed on extensive data sets ("big data"), has become very successful in tackling various challenges, for example, image interpretation, language recognition, autonomous decision making or stock market predictions. Several scientific disciplines have embraced the capability of modern machine learning algorithms, including astronomy and many fields of geosciences.

The field of geodesy has seen a significant increase in observational data in recent years, in particular from Global Navigation Satellite Systems (GNSS) with tens of thousands of high-quality permanent stations, multiple constellations, and increasing data rates. With the upcoming NISAR mission, the InSAR community needs to prepare for handling daily products exceeding 50 GB. In the future, the next-generation Very Long Baseline Interferometry (VLBI) Global Observing System (VGOS) will deliver unprecedented amounts of data compared to legacy VLBI operations. Traditional data processing and analysis techniques that rely largely on human input are not well suited to harvest such rich data sets to their full potential. Still, machine learning techniques are not yet adopted in geodesy.

Machine learning in geodesy has the potential to facilitate the automation of data processing, detection of anomalies in time series and image data, their classification into different categories and prediction of parameters into the future. Machine learning and, in recent years, deep learning methods can successfully model complex spatiotemporal data through the creation of powerful representations at hierarchical levels of abstraction. Furthermore, machine learning techniques provide promising results in addressing the challenges that arise when handling multi-resolution, multi-temporal, multi-sensor, multi-modal data.

The information contained in GNSS station position time series is essential as it can help derive important conclusions related to hydrology, earthquakes, or volcanism using machine learning. Other important applications are tropospheric and ionospheric parameters derived from GNSS where automated detection and prediction could be beneficial for improved severe weather forecasting and space weather monitoring, respectively. InSAR data will benefit in particular from efficient image processing algorithms based on machine learning, facilitating the detection of regions of interest. In several of these cases, the development of scalable deep learning schemes can contribute to more effectively handling and processing of large-scale spatiotemporal data.

Traditional machine learning techniques for geodetic tasks include convolutional neural networks for image data and recurrent neural networks for time series data. Typically, these networks are trained by supervised learning approaches, but certain applications related to autonomous processing will benefit from reinforcement learning.

The field of machine learning has expanded rapidly in recent years and algorithms are constantly evolving. It is the aim of this JSG to identify best practices, methods, and algorithms when applying machine learning to geodetic tasks. In particular, due to the “black box” nature of many machine learning techniques, it is very important to focus on appropriate ways to assess the accuracy and precision of the results, as well as to correctly interpret them.

Objectives

- Identify geodetic applications that could benefit from machine learning techniques, both in terms of which data sets to use and which issues to investigate.
- Create an inventory of suitable machine learning algorithms to address these problems, highlighting their strengths and weaknesses.
- Perform comparisons between machine learning methods and traditional data analysis approaches, e.g., for time series analysis and prediction.
- Focus on error assessment of results produced by machine learning algorithms.
- Identify open problems that come with the automation of data processing and generation of geodetic products, including issues of reliability.
- Develop best practices when applying machine learning methods in geodesy and establishing standardized terminology.

Program of Activities

- Create a web page about machine learning in geodesy to provide information and raise awareness about this topic. The page will include:
  - inventory of algorithms, see above,
  - benchmark datasets to test the performance of these algorithms,
  - comprehensive record of previous activities/ publications related to machine learning in geodesy,
  - description of activities by the JSG members.
- Work toward a state-of-the-art review paper about machine learning in geodesy co-authored by the JSG members.
- Promote sessions and presentation of the research results at international scientific assemblies (IAG/IUGG, EGU, AGU) and technique-specific meetings (IGS, IVS, ...).

Membership

Benedikt Soja (USA), chair
Kyriakos Balidakis (Germany)
Clayton Brengman (USA)
Jingyi Chen (USA)
Maria Kaselimi (Greece)
Ryan McGranaghan (USA)
Randa Natras (Germany)
Simone Scardapane (Italy)

JSG T.30: Dynamic modeling of deformation, rotation and gravity field variations

Chair: *Y. Tanaka* (Japan)
Affiliation: Commissions 2 and 3, GGOS

Introduction

Advancements in the Global Geodetic Observation System (GGOS), and terrestrial, aerial and marine geodetic observations have enabled us to monitor deformation, rotation and gravity field variations of the Earth with the unprecedented accuracy, which are caused by geophysical phenomena having various space-time scales. In addition, recent developments of global networks for solid-Earth observations and technologies for laboratory experiments have allowed us to obtain higher-quality and finer-resolution geophysical data for elasticity, density, viscosity, pressure, electromagnetic and thermal structures, etc., reflecting three dimensional heterogeneities in the internal Earth.

The improved geodetic and geophysical data motivate us to interpret the various phenomena, based on dynamic modelling. Through the modelling, we are able to identify the causes of the detected space-time variations and to deepen the understanding of the phenomena. Furthermore, it would help appeal the usefulness of GGOS.

This JSG consists of scientists working on dynamic modelling using diverse approaches. The targets of the modelling include local, regional and global variations which occur near the surface down to the inner core. To share different perspectives for modelling stimulates the activities of each member and can produce and/or evolve collaborative studies. For which reason, we form a forum within the ICCT.

Objectives

- Development/improvement of forward modelling:
  - Natural phenomena: earthquake, volcano, plate motion, surface fluids, glacial isostatic adjustment (GIA), tides and Earth rotation, etc.
  - Properties of the Earth structure to be modelled: elasticity, viscoelasticity, plasticity, poroelasticity, electromagnetic, thermal and chemical properties, heterogeneities and anisotropies in the Earth structure, etc.
  - Modelling approaches: analytical, semi-analytical and fully numerical methods and associated approximation methods, etc.
  - Comparison between different theories.
  - Opening developed software (if possible).
- Development or improvement of inversion and simulation methods:
  - Integration of diverse data.
  - Effective processing of a large quantity of data.
  - Data assimilation.
  - Application of various theories to real observations for new scientific findings.

Program of Activities

- To launch an e-mail list to share information concerning research results and to interchange ideas for solving related problems.
- To open a web page to share information, such as publication lists and its update.
- To promote international workshops focusing on the above research theme.
- To propel collaborations with closely related joint study groups such as geodetic, seismic and geodynamic constraints on glacial isostatic adjustment, cryospheric deformation and assessing impacts of loading on reference frame realizations.
- To have sessions at international meetings and workshops (EGU, AGU, IAG, Hotine-Marussi Symposium, etc.) as needed.

Membership

Shin-Chan Han (Australia)
Taco Broerse (Netherlands)
José Fernández (Spain)
Guangyu Fu (China)
Hom Nath Gharti (USA)
Pablo J. González (Spain)
Cheinway Hwang (Taiwan)
Volker Klemann (Germany)
Zdeněk Martinec (Ireland)
Daniel Melini (Italy)
Anthony Mémin (France)
Craig Miller (New Zealand)
Jun'ichi Okuno (Japan)
Riccardo Riva (Netherlands)
Jeanne Sauber (USA)
Giorgio Spada (Italy)
Yoshiyuki Tanaka (Japan), chair
Peter Vajda (Slovak Republic)
Wouter van der Wal (Netherlands)

JSG T.31: Multi-GNSS theory and algorithms

Chair: *A. Khodabandeh* (Australia)
Affiliation: Commissions 1 and 4, GGOS

Introduction

The family of modernized and recently-developed global and regional navigation satellite systems is being further extended by plentiful Low Earth Orbit (LEO) navigation satellites that are almost 20 times closer to Earth as compared to current GNSS satellites. This namely means that navigation sensory data with much stronger signal power will be abundantly available, being in particular attractive in GNSS-challenged environments. Next to the development of new navigation signal transmitters, a rapid growth in the number of mass-market GNSS and software-defined receivers would at the same time demand efficient ways of data processing in terms of computational power and capacity.

Such a proliferation of multi-system and multi-frequency measurements, that are transmitted and received by mixed-type sensing modes, raises the need for a thorough research into the future of next-generation navigation satellite systems, thereby appealing rigorous theoretical frameworks, models and algorithms that enable such GNSS-LEO integration to serve as a high-accuracy and high-integrity tool for Earth-, atmospheric- and space-sciences.

Objectives

The main objectives of this JSG are to:

- Identify and investigate challenges that are posed by the integration of multi-GNSS and LEO observations.
- Develop and study proper theory for GNSS integrity and quality control.
- Conduct an in-depth analysis of the mass-market GNSS sensory data such as those of smart-phones.
- Improve computational efficiency of GNSS parameter estimation and testing in the presence of a huge number of GNSS sensing nodes.
- Investigate the problem of high-dimensional integer ambiguity resolution and validation in a multi-system, multi-frequency landscape.
- Articulate theoretical developments and findings through the journals and conference proceedings.

Program of Activities

While the investigation will strongly be based on the theoretical aspects of the GNSS-LEO observation modelling and challenges, they will be also accompanied by numerical studies of both the simulated and real-world data. Given the expertise of each member, the underlying studies will be conducted on both individual and collaborative bases. The output of the group study is to provide the geodesy and GNSS communities with well-documented models and algorithmic methods through the journals and conference proceedings.

Membership

Amir Khodabandeh (Australia), chair
Ali Reza Amiri-Simkooei (Iran)
Gabriele Giorgi (Germany)
Bofeng Li (China)
Robert Odolinski (New Zealand)
Jacek Paziewski (Poland)
Dimitrios Psychas (The Netherlands)
Jean-Marie Sleewagen (Belgium)
Peter J.G. Teunissen (Australia)
Baocheng Zhang (China)

JSG T.32: High-rate GNSS for geoscience and mobility

Chair: *M. Crespi* (Italy)
Affiliation: Commissions 1, 3 and 4, GGOS

Introduction

Global Navigation Satellite Systems (GNSS) have become for a long time an indispensable tool to get accurate and reliable information about positioning and timing; in addition, GNSS are able to provide information related to physical properties of media passed through by GNSS signals. Therefore, GNSS play a central role both in geodesy and geomatics and in several branches of geophysics, representing a cornerstone for the observation and monitoring of our planet.

So, it is not surprising that, from the very beginning of the GNSS era, the goal was pursued to widen as much as possible the range in space (from local to global) and time (from short to long term) of the observed phenomena, in order to cover the largest possible field of applications, both in science and in engineering. Two additional primary goals were, obviously, to get this information with the highest accuracy and in the shortest time.

The advances in technology and the deployment of new constellations, after GPS (in the next few years the European Galileo, the Chinese Beidou and the Japanese QZSS will be completed) remarkably contributed to transform this *three-goals dream* in reality, but still remain significant challenges when very fast phenomena have to be observed, mainly if real-time results are looked for.

Actually, for almost 15 years, starting from the noble birth in seismology, and the very first experiences in structural monitoring, high-rate GNSS has demonstrated its usefulness and power in providing precise positioning information in fast time-varying environments. At the beginning, high-rate observations were mostly limited at 1 Hz, but the technology development provided GNSS equipment (in some cases even at low-cost) able to collect measurements at much higher rates, up to 100 Hz, therefore opening new possibilities, and meanwhile new challenges and problems.

So, it is necessary to think about how to optimally process this potential huge heap of data, in order to supply information of high value for a large (and increasing) variety of applications, some of them listed hereafter without the claim to be exhaustive: better understanding of the geophysical/geodynamical processes mechanics; monitoring of ground shaking and displacement during earthquakes, also for contribution to tsunami early warning; tracking the fast variations of the ionosphere; real-time controlling landslides and the safety of structures; providing detailed trajectories and kinematic parameters (not only position, but also velocity and acceleration) of high dynamic platforms such as airborne sensors, high-speed terrestrial vehicles and even athlete and sport vehicles monitoring.

Further, due to the contemporary technological development of other sensors (hereafter referred as ancillary sensors) related to positioning and kinematics able to collect high-rate data (among which MEMS accelerometers and gyros play a central role, also for their low-cost), the feasibility of a unique device for high-rate observations embedding GNSS receiver and MEMS sensors is real, and it opens, again, new opportunities and problems, first of all related to sensors integration.

In this respect, Android based mass-market devices (smartphones and tablets) are nowadays able to provide 1 Hz raw GNSS measurements (with a growing number of models able to provide multi-constellation and multi-frequency code and phase observations) in addition to the above-mentioned ancillary sensors measurements.

All in all, it is clear that high-rate GNSS (and ancillary sensors) observations represent a great resource for future investigations in Earth sciences and applications in engineering, meanwhile stimulating a due attention from the methodological point of view in order to exploit their full potential and extract the best information. This is the why it is worth to open a focus on high-rate (and, if possible, real-time) GNSS within ICCT.

Objectives

- To realize the inventories of:
  - the available and applied methodologies for high-rate GNSS, in order to highlight their pros and cons and the open problems
  - the present and wished applications of high-rate GNSS for science and engineering, with a special concern to the estimated quantities (geodetic, kinematic, physical), in order to focus on related problems (still open and possibly new) and draw future challenges
  - the technology (hw, both for GNSS and ancillary sensors, and sw, possibly FOSS), pointing out what is ready and what is coming, with a special concern for the supplied observations and for their functional and stochastic modeling with the by-product of establishing a standardized terminology.
- To address known (mostly cross-linked) problems related to high-rate GNSS as (not an exhaustive list): revision and refinement of functional and stochastic models; evaluation and impact of observations time-correlation; impact of multipath and constellation change; outlier detection and removal; issues about GNSS constellations interoperability; ancillary sensors evaluation, cross-calibration and integration.
- To address new problems and future challenges which arise from inventories.
- To investigate about the interaction with present real-time global (IGS-RT, EUREF-IP, etc.) and regional/local positioning services: how can these services support high-rate GNSS observations and, on reverse, how can they benefit of high-rate GNSS observations

Program of Activities

- To launch a questionnaire for the above mentioned inventory of methodologies, applications and technologies.
- To open a web page with information concerning high-rate GNSS and its wide applications in science and engineering, with special emphasis on exchange of ideas, raw relevant datasets, provision and updating bibliographic list of references of research results and relevant publications from different disciplines.
- To launch the proposal for two (one science and the other engineering oriented) state-of-the-art review papers in high-rate GNSS co-authored by JSG members.
- To promote sessions and presentation of research results at international symposia both related to Earth science (IAG/IUGG, EGU, AGU, EUREF, IGS), engineering (workshops and congresses in structural, geotechnical, mechanical, transport and automotive engineering), and life sciences (sports and health care).

Membership

Mattia Crespi (Italy), chair
Elisa Benedetti (United Kingdom)
Mara Branzanti (Switzerland)
Liang Chen (China)
Gabriele Colosimo (Switzerland)
Elisabetta D'Anastasio (New Zealand)
Roberto Devoti (Italy)
Rui Fernandes (Portugal)
Marco Fortunato (Italy)
Athanassios Ganas (Greece)
Pan Li (Germany)
Alain Geiger (Switzerland)
Jianghui Geng (China)
Dara Goldberg (USA)
Kathleen Hodgkinson (USA)
Shuanggen Jin (China)
Iwona Kudlacik (Poland)
Jan Kaplon (Poland)
Augusto Mazzoni (Italy)
Joao Francisco Galera Monico (Brazil)
Héctor Mora Páez (Colombia)
Michela Ravanelli (Italy)
Giorgio Savastano (Luxembourg)
Sebastian Riquelme (Chile)
Peiliang Xu (Japan)

JSG T.33: Time series in geodesy and geodynamics

Chair: *W. Kosek* (Poland)
Affiliation: Commissions 1, 3 and 4, GGOS

Introduction

Observations of the space geodesy techniques enable measuring Earth's gravity variations caused by mass displacement, the change in the Earth's shape, and the change in the Earth's rotation. The Earth's rotation represented by the Earth Orientation Parameters (EOP) should be observed with possibly the smallest latency to provide real-time transformation between the International Terrestrial and Celestial Reference Frames (ITRF and ICRF). Observed by GRACE missions, redistribution of mass within the fluid layers relative to the solid Earth induces exchange of angular momentum between these layers and solid Earth, changes in the Earth's inertia tensor.

Redistribution of masses induce temporal variations of Earth's gravity field where 1 degree spherical harmonics correspond to the Earth's centre of mass variations (long term mean of them determines the ITRF origin) and 2 degree spherical harmonics correspond to Earth rotation changes. Satellite altimetry enables observation of changes in geometry of sea level and space geodesy techniques enable observations of changes in geometry of the Earth's crust by monitoring horizontal and vertical deformations of site positions. Sea surface height varies due to thermal expansion of sea water and changes in ocean water mass arising from melting polar ice cap, mountain glacier ice, as well as due to groundwater storage. The site positions which are determined together with satellite orbit parameters (in the case of SLR, GNSS and DORIS) or radio source coordinates (in the case of VLBI) and Earth orientation parameters (x, y pole coordinates, UT1-UTC/LOD and precession-nutation corrections dX, dY) are then used to build the global ITRF which changes due to e.g. plate tectonics, postglacial rebound, atmospheric, hydrology and ocean loading and earthquakes. In these three components of geodesy which should be integrated into one unique physical and mathematical model there are changes that are described by spatial and temporal geodetic time series.

Different time series analysis methods have been applied to analyze all elements of the Earth's system for better understanding the mutual relationship between them. The nature of considered signals in the geodetic time series is mostly wideband, irregular and non-stationary. Thus, it is recommended to apply spectra-temporal analyzes methods to analyze and compare these series to explain the mutual interaction between them in different time and different frequency bands. The main problems to deal with is to estimate the deterministic (including trend and periodic variations) and stochastic (non-periodic variations and random changes described by different noise characters) components in these geodetic time series as well as to apply the appropriate methods of spectra-temporal comparison of these series.

The multiple methods of time series analysis may be encouraged to be applied to the preprocessing of raw data from various geodetic measurements in order to promote the quality level of enhancement of signals existing in these data. The topic on the improvement of the edge effects in time series analysis should be also considered, since they may affect the reliability of long-range tendency (trends) estimated from data series as well as the real-time data processing and prediction. For coping with small geodetic samples one can apply simulation-based methods and if the data are sparse, Monte-Carlo simulation or bootstrap technique may be useful.

Measurements by space geodetic techniques provide an important contribution to the understanding of climate change. The analysis of Earth rotation and geophysical time series as well as global sea level variations shows that there is a mutual relationship between them for oscillations with periods from a few days to decades. The thermal annual cycle caused by the Earth's orbital motion modified by variable solar activity induces seasonal variations the Earth's fluid layers, thus in the Earth rotation, sea level variations as well as in the changes of the Earth's gravity field and centre of mass. The interrelationships between the geodetic time series and changes of global troposphere temperature show that they provide very important information about the Earth's climate change (for example global sea level increases faster during El Nino events associated with the increase of global temperature and in this time the increase of length of day can be also noticed). Thus, the spectra-temporal analysis and comparison of geodetic time series should also include time series associated with solar activity.

Objectives

- Study of the nature of geodetic time series to choose optimum time series analysis methods for filtering, spectral analysis, time frequency analysis and prediction.
- Study of Earth's geometry, rotation and gravity field variations and their geophysical causes in different frequency bands.
- Evaluation of appropriate covariance matrices for the time series by applying the law of error propagation to the original measurements, including weighting schemes, regularization, etc.
- Determination of the statistical significance levels of the results obtained by different time series analysis methods and algorithms applied to geodetic time series.
- Comparison of different time series analysis methods in order to point out their advantages and disadvantages.
- Application and development of time frequency analysis methods to detect the relationship between geodetic time series and time series associated with the solar activity in order to solve the problems related to the climate change.
- Recommendations of different time series analysis methods for solving problems concerning specific geodetic time series.
- Detection of reliable station velocities and their uncertainties with taking into account their non-linear motion and environmental loadings and identification of site clusters with similar velocities
- Deterministic and stochastic modelling and prediction of troposphere and ionosphere parameters for real time precise GNSS positioning.
- Better Earth Orientation Parameters short-term prediction using the extrapolation models of the fluid excitation functions.

Program of Activities

- Organization of a session on time series analysis in geodesy at the Hotine-Marussi Symposium in 2022.
- Co-organization of the PICO sessions "Mathematical methods for the analysis of potential field data and geodetic time series" at the European Geosciences Union General Assemblies in Vienna, Austria.

Membership

Wieslaw Kosek (Poland), chair
Orhan Akyilmaz (Turkey)
Johannes Boehm (Austria)
Xavier Collilieux (France)
Olivier de Viron (France)
Laura Fernandez (Argentina)
Richard Gross (USA)
Mahmut O. Karslioglu (Turkey)
Anna Kłos (Poland)
Hans Neuner (Germany)
Tomasz Niedzielski (Poland)
Sergei Petrov (Russia)
Waldemar Popiński (Poland)
Michael Schmidt (Germany)
Michel Van Camp (Belgium)
Jan Vondrák (Czech Republic)
Dawei Zheng (China)
Yonghong Zhou (China)

JSG T.34: High-resolution harmonic series of gravitational and topographic potential fields

Chair: *S. Claessens* (Australia)
Affiliation: Commission 2 and GGOS

Introduction

The resolution of models of the gravitational and topographic potential fields of the Earth and other celestial bodies in the Solar System has increased steadily over the last few decades. These models are most commonly represented as a spherical, spheroidal or ellipsoidal harmonic series. Harmonic series are used in many other areas of science such as geomagnetism, particle physics, planetary geophysics, biochemistry and computer graphics, but geodesists are at the forefront of research into high-resolution harmonic series.

In recent years, there has been increased interest and activity in high-resolution harmonic modelling (to spherical harmonic degree and order (d/o) 2190 and beyond). In 2019, the first model of the Earth's gravitational potential in excess of d/o 2190 was listed by the International Centre for Global Earth Models (ICGEM). All high-resolution models of gravitational potential fields rely on forward modelling of topography to augment other sources of information. Harmonic models of solely the topographic potential are also becoming more common. Models of the Earth's topographic potential up to spherical harmonic d/o 21,600 have been developed, and ICGEM has listed topographic gravity field models since 2014.

The development of high-resolution harmonic models has posed and continues to pose both theoretical and practical challenges for the geodetic community.

One challenge is the combination of methods for ultra-high d/o harmonic analysis (the forward harmonic transform). Least-squares-type solutions with full normal equations are popular, but computationally prohibitive at ultra-high d/o. Alternatives are the use of block-diagonal techniques or numerical quadrature techniques. Optimal combination and comparison of the different techniques, including studying the influence of aliasing, requires further study.

A related issue is the development of methods for the optimal combination of data sources in the computation of high-degree harmonic models of the gravitational potential. Methods used for low-degree models cannot always suitably be applied at higher resolution.

Another challenge is dealing with ellipsoidal instead of spherical geometry. Much theory has been developed and applied in terms of spherical harmonics, but the limitations of the spherical harmonic series for use on or near the Earth's surface have become apparent as the maximum d/o of the harmonic series has increased. The application of spheroidal or ellipsoidal harmonic series has become more widespread, but needs further theoretical development.

A specific example is spectral forward modelling of the topographic potential field in the ellipsoidal domain. Various methods have been proposed, but these are yet to be compared from both a theoretical and numerical standpoint. There are also still open questions about the divergence effect and the amplification of the omission error in spherical and spheroidal harmonic series inside the Brillouin surface.

A final challenge are numerical instabilities, underflow/overflow and computational efficiency problems in the forward and reverse harmonic transforms. Much progress has been made on this issue in recent years, but further improvements may still be achieved.

Objectives

The objectives of this JSG are to:

- Develop and compare combined full least-squares, block-diagonal least-squares and quadrature approaches to very high-degree and order spherical, spheroidal and ellipsoidal harmonic analysis.
- Develop and compare methods to compute high-resolution harmonic potential models using ellipsoidal geometry, either in terms of spherical, spheroidal or ellipsoidal harmonic series.
- Study the divergence effect of ultra-high degree spherical, spheroidal and ellipsoidal harmonic series inside the Brillouin sphere, spheroid and/or ellipsoid.
- Study efficient methods for ultra-high degree and order harmonic analysis (the forward harmonic transform) for a variety of data types and boundary surfaces, as well as harmonic synthesis (the reverse harmonic transform) of various quantities.

Program of Activities

To facilitate achievement of these objectives, the group will provide a platform for increased collaboration between group members, encouraging exchange of ideas and research results. Working meetings of group members will be organized at major international conferences.

Membership

Sten Claessens (Australia), chair
Hussein Abd-Elmotaal (Egypt)
Blažej Bucha (Slovakia)
Christoph Förste (Germany)
Toshio Fukushima (Japan)
Ropesh Goyal (India)
Christian Hirt (Germany)
Norbert Kühtreiber (Austria)
Kurt Seitz (Germany)
Elmas Sinem Ince (Germany)
Michal Šprlák (Czech Republic)
Philipp Zingerle (Germany)

JSG T.35: Advanced numerical methods in physical geodesy

Chair: *R. Čunderlík* (Slovakia)
Affiliation: Commission 2 and GGOS

Introduction

Advanced numerical methods and high performance computing (HPC) facilities provide new opportunities in many applications in geodesy. The goal of this JSG is to apply such numerical methods to solve various problems of physical geodesy, mainly gravity field modelling, processing satellite observations, nonlinear data filtering or others. It focuses on a further development of approaches based on discretization numerical methods like the finite element method (FEM), finite volume method (FVM) and boundary element method (BEM) or the meshless collocation techniques like the method of fundamental solutions (MFS) or singular boundary method (SOR). Such approaches allow gravity field modelling in spatial domain while solving the geodetic boundary-value problems (GBVPs) directly on the discretized Earth's surface. Their parallel implementations and large-scale parallel computations on clusters with distributed memory allow high-resolution numerical modelling.

The JSG is also open to new innovative approaches based for example on the computational fluid dynamics (CFD) techniques, spectral FEM, advection-diffusion equations, or similar approaches of scientific computing. It is also open for researchers dealing with classical approaches of gravity field modelling like the spherical or ellipsoidal harmonics that are using HPC facilities to speed up their processing of enormous amount of input data. This includes large-scale parallel computations on massively parallel architectures as well as heterogeneous parallel computations using graphics processing units (GPUs).

Objectives

The objectives of this JSG are to:

- Design the FEM, BEM and FVM numerical models for solving GBVPs with the oblique derivative boundary conditions.
- Develop algorithms for a discretization of the Earth's surface based on adaptive refinement procedures (the BEM approach).
- Develop algorithms for an optimal construction of 3D unstructured meshes above the Earth's topography (the FVM or FEM approaches).
- Design numerical models based on MFS or SBM for processing the GOCE gravity gradients in spatial domain.
- Design algorithms for 1D along track filtering of satellite data, e.g., from the GOCE satellite mission.
- Develop numerical methods for nonlinear diffusion filtering of data on the Earth's surface based on solutions of the nonlinear heat equations.
- Investigate innovative approaches based on the computational fluid dynamics (CFD) techniques, spectral FEM or advection-diffusion equations.
- Apply parallel algorithms using MPI procedures.
- Apply large-scale parallel computations on clusters with distributed memory.

Program of Activities

- Active participation in major geodetic conferences.
- Working meetings at international symposia.
- Organization of a conference session.

Membership

Róbert Čunderlík (Slovakia), chair
Petr Holota (Czech Republic)
Michal Kollár (Slovakia)
Marek Macák (Slovakia)
Matej Medľa (Austria)
Karol Mikula (Slovakia)
Zuzana Minarechová (Slovakia)
Otakar Nesvadba (Czech Republic)
Yoshiyuki Tanaka (Japan)
Robert Tenzer (Hong Kong)
Zhi Yin (Germany)

JSG T.36: Dense troposphere and ionosphere sounding

Chair: *G. Savastano* (Luxembourg)
Affiliation: Commission 4 and GGOS

Introduction

Global Navigation Satellite Systems Radio Occultation (GNSS-RO) have become an important technique to globally sound the Earth's atmosphere from space. This technique overcomes some of the main limitations of ground-based remote sensing instruments, increasing the amount of tropospheric and ionospheric data measured over the oceans and under sampled regions.

Up until few years ago, GNSS-RO observations were mainly supported by expensive satellite missions (e.g. COSMIC-1), which implies also considerably high operational costs. A great opportunity was brought in the field by nanosatellites, which are a satellite of low mass and size, usually under 500 kg. These satellites can significantly reduce the large economic cost of launch vehicles and the costs associated with construction.

In recent years, commercial RO providers (e.g., Spire Global) shifted the paradigm and started operationally producing GNSS-RO data from CubeSats in Low Earth Orbit (LEO). This data was demonstrated to be comparable in quality to larger satellite constellations (e.g., COSMIC-1), but with a denser spatial and temporal coverage. The new paradigm proposed by these commercial companies is that nanosatellites, especially in large numbers, may be more beneficial than using fewer, larger satellites in tasks such as gathering scientific data.

Independent assessments of these commercial data quality were carried out by JPL, UKMO, ESA, NOAA, and NRL, which convinced the international RO community that commercial data are ready to be assimilated by NWP centres and used by scientists to investigate different research topics.

Often, these nanosatellites carry different scientific payloads collecting a large amount of different data (e.g., GNSS-POD solutions, GNSS top ionosphere TEC observations), that could be exploited for several scientific investigations. Furthermore, contemporary technological advances of other low-cost sensors (e.g., in-situ atmospheric sensors, MEMS accelerometers and gyros) opens new opportunity and problems, first of all related to data fusion, validation and sensor integration.

Spire will share data samples (e.g., podGps, atmPhs, podTec, atmPrf) within the members of the study group, in order to promote the development of new algorithms and methodologies for remote sensing of the Earth.

It is clear that this unprecedented dense coverage of troposphere and ionosphere sounding enabled by commercial GNSS-RO CubeSats and dense network of ground-based GNSS receivers represents a great opportunity for future investigations in Earth sciences. This brings the attention to the methodological point of view in order to exploit their full potential and extract the best information. This is the reason why it is worth opening a focus on dense troposphere and ionosphere sounding using GNSS-RO and ground-based GNSS techniques within ICCT.

Objectives

- To realize inventories of:
  - commercial and publicly available GNSS-RO and ground-based GNSS observations, with a distinction between troposphere and ionosphere observations, and a classification based on the different acquisition parameters (e.g., sampling rate, vertical or temporal resolution, altitude range of acquisition, tracking mode),
  - present and wished applications of dense troposphere and ionosphere sounding for science and engineering, with a special concern to the estimated physical quantities (e.g., temperature, pressure and TEC), in order to focus on related problems (still open and possibly new) and draw future challenges.
- To address known problems related to dense troposphere and ionosphere sounding using GNSS-RO observations as (not an exhaustive list): atmospheric anomalies detection, localization and classification; revision and refinement of inversion techniques; temporal variability of receivers DCBs and evaluation of their impact in the calibrated process; data quality assessment and validation; outlier detection and removal; in-situ sensors evaluation, cross-calibration and integration.
- To describe the different analytical and physical implication of combining observations collected with different observational geometries, such as: ground-based receivers tracking signals transmitted by GNSS satellites in MEO and GEO orbits; space-based receivers tracking GNSS signals at different elevation angles (from positive to negative and vice versa). Furthermore, investigate the different ways of combining together these remote sensing observations to retrieve fundamental atmospheric parameters, and disentangle the spatial and temporal variability of the atmosphere.

Program of Activities

- To organize a session at the forthcoming Hotine-Marussi symposium 2022.
- To convene at international conferences such as IAG/IUGG, EGU, AGU.

Membership

Giorgio Savastano (Luxembourg), chair
Matthew Angling (UK)
Elvira Astafyeva (France)
Riccardo Biondi (Italy)
Mattia Crespi (Italy)
Kosuke Heki (Japan)
Addisu Hunegnaw (Luxembourg)
Alessandra Mascitelli (Italy)
Giovanni Occhipinti (France)
Michela Ravanelli (Italy)
Eugenio Realini (Italy)
Lucie Rolland (France)
Felix Norman Teferle (Luxembourg)
Jens Wickert (Germany)

JSG T.37: Theory and methods related to combination of high-resolution topographic/ bathymetric models in geodesy

Chair: **D. Carrion** (Italy)
Affiliation: Commission 2 and GGOS

Introduction

Topographic and bathymetric models constitute a fundamental input for geodetic computations, e.g. for the evaluation of terrain effects for local and global geoid estimation. In this regard, the Shuttle Radar Topography Mission (SRTM) provided a very significant contribution to the knowledge of terrain heights over land. Great advantages provided by SRTM are the homogeneity of its spatial resolution and its (almost) global coverage. In addition, the spatial resolution of SRTM is adequate for the majority of geodetic applications.

The situation is quite different concerning currently available bathymetric models: in this case, the resolution is not homogeneous around the Earth and the level of accuracy can vary considerably from one area to another. In addition, when considering the transition between land surface and sea bottom, the combination of topographic and bathymetric models can be challenging, due to the limitations linked to resolution and accuracy of data and to local datum inconsistencies, which could be neglected in global models.

Different combined products are available at global level, such as SRTM+, however the poor knowledge of the sea bottom or datum issues, may lead to problems in geodetic computations and should be further investigated. Apart from geodetic applications, the precise knowledge of the land-sea transition is crucial for modelling of other environmental processes in the coastal zone, such as the impact of sea level change and extreme sea level events such as storm surges and tsunamis.

This JSG aims at studying the available topographic and bathymetric models and at exploring their limitations, in particular concerning the transition along the coasts.

Objectives

- Highlight the issues of the topography/sea bottom transition through literature examples.
- Analyse available data on global and local topographic and bathymetric models, highlighting the issues, based also on personal research experience.
- Verify the quality of the transition through test cases.
- Suggest best practices for combination of models.
- Identify the need for data acquisition in specific areas.

Program of Activities

- Explore available data and literature research.
- Propose review papers concerning the state of the art knowledge on the combination of topographic and bathymetric models.
- Cooperate with IAG Commissions and other JSGs.
- Organize meetings, workshops and sessions at selected conferences, e.g. during Hotine-Marussi 2022.

Membership

Daniela Carrion (Italy), chair
Riccardo Barzaghi (Italy)
Mattia Crespi (Italy)
Vassilios Grigoriadis (Greece)
Karsten Jacobsen (Germany)
Kevin Kelly (US)
Michael Kuhn (Australia)
Cornelis Slobbe (Netherlands)
Roberto Teixeira Luz (Brazil)
Ana Cristina de Matos (Brazil)
Dan Palcu (Brazil)
Ionut Sandric (Romania)
Georgios S. Vergos (Greece)

Inter-Commission Committee on Geodesy for Climate Research (ICCC)

President: **Annette Eicker** (Germany)
Vice-President: **Carmen Boening** (USA)

Internet site: https://iccc.iag-aig.org/
Twitter: @IAG_climate

Terms of Reference

The Inter-Commission Committee on Geodesy for Climate Research (ICCC) was formally approved and established during the 27th IUGG General Assembly in Montreal 2019 to advance the use of geodetic observations for climate research.

The growing data record from numerous geodetic observation techniques (GNSS station observations, satellite radio occultation and reflectometry, satellite gravimetry, satellite altimetry, InSAR, VLBI, GNSS-controlled tide gauges, etc.) provides a new quantitative view on various variables that are relevant for climate research, such as tropospheric water vapor, thermospheric neutral density, terrestrial water storage, ice sheet and mountain glacier mass , steric and barystatic sea level, sea surface winds, ocean waves, subsurface and surface currents, or sea ice extent and -thickness. Many of these are listed as Essential Climate Variables (ECV) according to the definition by the Global Climate Observing System (GCOS).

Geodetic methods provide unique information on the Earth's surface geometry, its large-scale mass transports such as fluctuations in Earth’s water cycle, and the global energy imbalance. Time series of geodetic data start to reveal a complex picture of natural climate variability, long-term climate change and anthropogenic modifications. Combined with other observations by means of, e.g., global or regional Earth system simulations or reanalyses, they provide excellent tools to improve our understanding of climate-related processes. Furthermore, due to their advantage of being independent of other data commonly used to drive and evaluate coupled climate models, geodetic observations have strong potential for either being used as input for numerical models as constraints (e.g. water budget, sea level budget) or for a posteriori model assessment.

While it is generally recognized that geodetic data provide invaluable information for studying the planet’s changing climate, programmatic obstacles, technical limitations such as the length of time series, and scientifically open questions have been identified that hamper the broader recognition of geodesy as an important source of information for climate research. In order to better promote and facilitate the use of genuinely geodetic data in the climate community, and to better explore the synergies between the different geodetic branches with respect to observing climate signals, we propose to establish an Inter-Commission Committee on “Geodesy for Climate Research”. It will be based on the work started in the 2015-2019 IAG period’s Joint Working groups 2.6.1 “Geodetic Observations for Climate Model Evaluation” and 4.3.8 “GNSS Tropospheric Products for Climate”. It will continue the roadmap initiated at the workshop “Satellite Geodesy for Climate Studies” (Bonn 2017), which brought together geodesists representing all different observation techniques and climate scientists in a dedicated framework.

The topic of the suggested ICC is positioned at the interface between geodesy and climate science and is of high relevance for the entire scientific discipline geodesy. Various geodetic observables provide complementary information on climate change processes. Examples include (but are not limited to) the following: climate change related mass transport (e.g. ice melting, sea level rise, changes in the continental and oceanic water cycle as well as their impact on water resources) are among the primary signals derived from (satellite) gravity observations and can also be detected directly by geometrical measurements of volume change (satellite altimetry for water bodies/ice, InSAR over aquifers) or indirectly via crustal deformations induced by surface loads (terrestrial GNSS, InSAR, VLBI). Furthermore, by changing the Earth's moments of inertia and relative momentum term, mass transports also lead to measurable variations in Earth orientation parameters.

Climate change related variations of the atmosphere affect the propagation of geodetic signals and thus can be inferred from long time series of VLBI and ground and satellite based GNSS observations. Finally, a stable global geodetic reference frame (GGRF) is an indispensable requirement for providing a uniform reference for monitoring global change processes, as has recently been recognized by the corresponding UN resolution[1]. However, synergies between the different geodetic observing systems for monitoring climate change have not yet been fully exploited and the interaction with the climate communities needs to be intensified in order to achieve a broader – and better recognized – use of geodetic data for climate research.

Objectives

- To deepen the understanding of the potential (and limitations) of geodetic measurements for the observation, analysis and identification of climate signals
- To advance the development of geodetic observing systems, analysis techniques and data products regarding their sensitivity to and impact on Essential Climate Variables, this way also supporting activities of the IPCC
- To advance the improvement of numerical climate models, climate monitoring systems, and climate reanalysis efforts through incorporating geodetic observations
- To stimulate scientific exchange and collaboration between the geodetic and the climate science communities
- To make geodetic variables more user-friendly by sharing them publicly and explaining their usefulness

Program of Activities (tentative):

- The ICC will establish a workshop series to intensify the exchange between different geodetic communities and the climate monitoring and modeling communities.
- The ICC will create opportunities for communication and discussion through suggesting/organizing sessions at international scientific meetings and conferences.
- The ICC will develop reference (best-practice) methods for evaluating/improving climate models with geodetic data and publish these methods (e.g. in a 'white paper').
- The ICC will seek to organize special issues on its topic in appropriate international journals.
- The ICC will work towards a better recognition of geodesy as an essential provider of precise information about long-term changes in the Earth system.
- The ICC will establish links to other climate science related bodies, e.g. the IUGG Union Commission on Climatic and Environmental Change (CCEC) or the IAMAS International Commission on Climate (ICCL).
- The ICC will maintain a website for dissemination of ICC related information

List of Joint Working Groups:

JWG C.1: Climate Signatures in Earth Orientation Parameters
Chair: *Jolanta Nastula* (Poland)
Vice-Chair: *Henryk Dobslaw* (Germany)
(Affiliation: Commission 3, GGOS, IERS)

JWG C.2: Quality control methods for climate applications of geodetic tropospheric parameters
Chair: *Rosa Pacione* (Italy)
Vice-Chair: *Marcelo Santos* (Canada)
(Affiliation: Commission 4, IGS, IVS)

JWG C.3: Geodesy for the Cryosphere: advancing the use of geodetic data in polar climate modelling
Chair: *Bert Wouters* (Netherlands)
Vice-Chair: *Ingo Sasgen* (Germany)
(Affiliation: Commission 2, Commission 3, GGOS)

JWG C.4: Sea level and vertical land motion
Chair: *Roelof Rietbroek* (Germany)
Vice-Chair: *Riccardo Riva* (Netherlands)
(Affiliation: Commission 1, 2 & 4, GGOS)

JWG C.5: Understanding the monsoon phenomenon from a geodetic perspective
Chair: *Balaji Devaraju* (India)
Vice-Chair: *Matthias Weigelt* (Germany)
(Affiliation: Commissions 2, 3 & 4, GGOS)

JWG C.6: Numerical Simulations for Recovering Climate-Related Mass Transport Signals
Chair: *Roland Pail* (Germany)
Vice-Chair: *Wei Feng* (China)
(Affiliation: Commission 2, GGOS, IGFS)

JWG C.7: Satellite geodetic data assimilation for climate research
Chair: *Mehdi Khaki* (Australia)
(Affiliation: Commission 2, GGOS)

JWG C.8: Methodology of comparing/validating climate simulations with geodetic data
Chair: *Jürgen Kusche* (Germany)
(Affiliation: Commisison 2, ICCT)

Steering Committee:

President: *Annette Eicker* (Germany)
Vice-President: *Carmen Boening* (USA)
Representative of Comm.1: *Christopher Kotsakis* (Greece)

Representative of Comm.2: *Wei Feng* (China)
Representative of Comm.3: *M. Schindelegger* (Germany)
Representative of Comm.4: *Anna Klos* (Poland)
Representative of GGOS: *Mayra Oyola* (USA)
Representative of IAMAS: *Vincent Humphrey* (USA)
Member at Large: *Felipe Nievinski* (Brazil)

Joint Working Groups

Joint Working Group JWG C.1: Climate Signatures in Earth Orientation Parameters

Affiliation: Commission 3, GGOS, IERS
Chair: *Jolanta Nastula* (Poland)
Vice-Chair: *Henryk Dobslaw* (Germany)

Introduction

Earth orientation parameters comprising variations of both the position of the rotational pole and the spin rate are precisely observed by modern space geodetic techniques for several decades already. Moreover, optical astrometric observations extending back in time over more than 100 years provide even carry information about the mass transport and mass distribution processes acting on Earth at historical times that might be explored to quantify slow and subtle variations in the Earth's climate. This working group will study the various contributors of the global and interactively coupled climate system to the observed changes of the Earth's orientation on time-scales from days to centennials. It will explore possibilities to validate numerical climate models and its individual components by means of assessing the angular momentum budget and the associated torques. The working group will further investigate predictive limits of various Earth system state and flux variables in order to aid short- and long-term prediction of polar motion and changes in the length-of-day, and might ultimately foster the incorporation of Earth Orientation Parameters into contemporaneous global re-analyses of the Earth System by means of data assimilation.

Objectives

- Detection of climatic signals in Earth's rotation from days to centennials
- Modelling of climatic trends on the Earth rotation from days to centennials
- Assessment of angular momentum budgets of global numerical climate and Earth system models
- Fusion of Earth rotation parameters and global geophysical fluid models by means of data assimilation

Activities

- Establishment of the "best practices" for deriving angular momentum and torque estimates from numerical climate model data
- Contributions to the future development of the Global Geophysical Fluid Centre (GGFC) of the International Earth Rotation and Reference Systems Service (IERS)
- Active participation at major geodetic conferences via both session proposals and contributing abstracts
- Annual working group meetings aligned to a major geodetic conference

Members

Christian Bizouard (France)
Sigrid Boehm (Austria)
Aleksander Brzezinski (Poland)
Benjamin Fong Chao (Taiwan)
Yavor Chapanov (Bulgaria)
Jianli Chen (USA)
Alexandre Couhert (France)
Robert Dill (Germany)
Alberto Escapa (Spain)
José Manuel Ferrandiz (Spain)
Laura Fernandez (Argentina)
Franziska Goettl (Germany)
Richard Gross (USA)
Robert Heinkelmann (Germany)
Sébastien Lambert (France)
Vladimir Pashkevich (Russia)
Elena Podladchikova (Belgium)
Cyril Ron (Czech Republic)
David Salstein (USA)
Michael Schindelegger (Germany)
Nikolay Sidorenkov (Russia)
Leonid Zotov (Russia)

Joint Working Group JWG C.2: Quality control methods for climate applications of geodetic tropospheric parameters

Chair: *Rosa Pacione* (Italy)
Vice-Chair: *Marcelo Santos* (Canada)
Affiliation: Commission 4, IGS, IVS

Introduction

Zenith Total Delay (ZTD) estimates are determined on a regular basis by several processing centers. For example, the IGS Analysis Centers have all their own independent ZTD solutions but, unlike other estimated parameters (e.g., orbits and satellite clocks) they are not combined. The official IGS

ZTD product is the result of an independent and dedicated solution based on a precise point positioning solution. On the other hand, EUREF performs combination of ZTD estimates on a regular basis as well as the IVS, which combines ZTD estimates coming from VLBI sessions. Nonetheless, not all IGS and IVS analysis centers make available their ZTD estimates. GNSS is reaching the "maturity age" of 30 years when climate normals of ZTD and gradients can be derived. But what would be the best series to serve the climate community? What series would offer the most realistic trends? As the IGS moves towards its third reprocessing campaign (REPRO3) where all ACs are to be make available their own ZTD and gradient estimates, as the IVS is moving towards its ACs also providing ZTD and gradient estimates and as the PPP-derived IGS product continues to be produced, there is a huge opportunity to perform quality control, using the tools of combination of parameters, to assess what would be the ZTD and gradient product best suited to be made available to climate studies.

Objectives

Potential scientific questions include:

- Are there advantages of combining ZTD estimates over not combining them? Is there any 'loss of information' in performing combinations?
- Would there be difference in trends derived from them? If so, how much implication for feeding information to climate?
- Can we trust in a combined ZTD as we trust any combined products (e.g., orbits, clock, site coordinates)?
- What the best combination strategy can be done (not necessarily to combine exactly the same way as other products)?
- Under what criteria can we use spectral analysis to demonstrate that a 'good' combined product have the same properties of the contributing solutions?
- What metrics should be used to ascertain that the optimal set of ZTD estimates, gradients and their trends, are provided to the climate community?

Activities

- Collaborate with IGS and IVS in the forthcoming reprocessing campaign.
- Participate actively in IAG, AGU and EGU conferences and organize sessions
- Organize working group meetings, splinter group meetings at the said symposia

Members

Fadwa Alshawaf (Germany)
Kyriakos Balidakis (Germany)
Sharyl Byram (USA)
Galina Dick (Germany)
Gunnar Elgered (Sweden)
Olalekan Isioye (South Africa)
Jonathan Jones (UK)
Michal Kačmařík (Czech Republic)
Anna Klos (Poland)
Haroldo Marques (Brazil)
Thalia Nikolaidou (Canada)
Tong Ning (Sweden)
Mayra Oyola (USA)
Eric Pottiaux (Belgium)
Paul Rebischung (France)
Roeland Van Malderen (Belgium)
Yibin Yao (China)

Joint Working Group JWG C.3: Geodesy for the Cryosphere: advancing the use of geodetic data in polar climate modelling

Affiliation: GGOS, Commission 2 & 3
Chair: *Bert Wouters* (Netherlands)
Vice-Chair: *Ingo Sasgen* (Germany)

Introduction

Over the last two decades, tremendous progress has been made in the development and use of geodetic methods to observe the rapidly emerging changes in the cryosphere. Variations in mass, elevation, grounded ice extent and flow speed are now being monitored on a routine basis using geodetic techniques such as gravimetry, (In)SAR, altimetry, GNSS and the like. Additionally, observations of land motion provide indirect information on the past evolution of ice masses. These geodetic observations have led to a leap forward in our understanding of the cryosphere as part of the climate system, and unambiguously have shown that the Earth's ice sheets and glaciers are increasingly losing mass and now represent the largest land-based contribution to global mean sea level rise.

Yet, compared to other fields of climate science (e.g. hydrology, oceanography and atmospheric sciences), inclusion of geodetic data is lagging behind in cryosphere modelling and remains mostly limited to validation of model output at large spatial scales. Data assimilation and the combination of multiple observables are still at an early development stage and rarely used to exploit the full potential of the geodetic measurements. To date, it remains a challenge incorporate the geodetically observed transitions in the cryosphere into future simulations. Within this JWG, we aim to bridge the currently existing gap between the geodetic and modelling communities, as detailed in our objectives below.

Objectives

Within this JWG, we aim to:

- identify current bottlenecks in using geodetic data for validation and assimilation efforts in ice sheet and glacier modelling
- communicate the possibilities and limitations of geodetic data to the modelling community
- document the wishes of the modelling community for geodetic data (resolution, projection, uncertainty definitions, etc.)
- identify geodetic data relevant for the evaluation of projection ensembles
- based on the above, list a set of recommendations for the geodetic community to advance the use geodetic data in modelling efforts.
- Explore potential of future geodetic observables for their use in glaciology

Program of Activities

- Summarize and gather state-of-the-art papers on geodetic observation techniques and data on the IAG website for non-geodetic audiences
- In close collaboration with the representatives of the cryosphere modelling community or through a open survey, identify requirements and derive concepts of geodetic data assimilation into ice sheet and glacier modelling
- List a set of recommended processing steps and standards for the geodetic community on the IAG website or in a white paper
- Schedule a yearly strategic splinter meeting to review progress and define strategic tasks for the upcoming year
- Acknowledge and promote work of talented young scientist contributing into the aims of JWG, through a yearly award or promotion on the ICCC website
- Communicate activities through IAG's social media accounts

Members

Mike Bevis (USA)
Matthias Braun (Germany)
William Colgan (Denmark)
Christoph Dahle (Germany)
Olga Engels (Germany)
Xavier Fettweis (Belgium)
Dana Floricioiu (Germany)
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Jan Lenaerts (USA)
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Malcolm McMillan (UK)
Brice Noël (Netherlands)
Masashi Niwano (Japan)
Louise Sandberg Sørensen (Denmark)
Mirko Scheinert (Germany)
Nicole Schlegel (USA)
David Wiese (USA)

Joint Working Group JWG C.4: Regional Sea level and vertical land motion

Affiliation: Commissions 1, 2 & 4, GGOS
Chair: *Roelof Rietbroek* (Germany)
Vice-Chair: *Riccardo Riva* (Netherlands)

Introduction

Global mean sea-level change is an excellent overall indicator of the state of the climate and the cryosphere, but societal impact is better represented by regional to local sea-level change, which can be very different from the global mean. Regional sea-level change may be more accurately described by dedicated time series, which incorporate knowledge of the designated coastal zone and vertical land motion. The non-uniform response of sea level to terrestrial mass changes causes regions in the far field of melting glaciers and ice sheets to be more sensitive to mass loss. Furthermore, long-term changes in wind fields, ocean heat uptake and circulation can change regional sea level. Finally, the difference between relative and geocentric sea level can be significant in places where vertical land motion is present. This can be caused by the ongoing glacial isostatic adjustment of the solid earth, but also by local subsidence from groundwater extraction and sediment compaction and loading.

The construction of sea-level change records which reconcile satellite measurements (e.g. radar altimetry, satellite gravimetry, lidar) with terrestrial measurements (GNSS stations, tide gauges and terrestrial gravimetry) on both global and regional level remains a challenging topic. This working group aims to increase the understanding of local/regional geophysical signals present in geodetic measurements, with the aim of encouraging a more widespread use of geodetic datasets in multi-disciplinary fields.

Objectives

- Encourage the use of geodetic datasets for multi-disciplinary studies related to sea-level changes.
- Communicate the need for a consistent treatment of observations and models of sea-level change and vertical land motion to non-geodetic scientific communities.

- Advance the science of regional and global sea-level research by identifying open questions and gathering state-of-the-art work.
- Communicate and coordinate activities with other relevant working groups (specifically: Geodesy for the Cryosphere), in particular on the topic of vertical land motion.

Program of Activities

- Summarize and gather state-of-the-art papers on sea level on the IAG website for non-geodetic audiences.
- Create an inventory of geodetic datasets useful for sea-level research, to be organised according to agreed standards and made freely available. Provide and gather, under a creative commons license, free to use visuals for communicating aspects of (regional) sea-level change and its (geodetic) observing system.
- Schedule a yearly strategy meeting to review the past year and define tasks for the upcoming year.
- Organize inter-JWG communication directly related to the study of vertical land motion, involving participants from the JWG Geodesy for the Cryosphere (e.g., shared web-page on IAG site, mutual participation in yearly strategy meetings).
- Communicate activities through IAG's social media accounts.
- Report activities back to relevant IAG working groups.

Members

Adrian Borsa (USA)
Francisco Calafat (UK)
Don Chambers (USA)
Sönke Dangendorf (Germany)
Thomas Frederikse (USA)
Ropesh Goyal (India)
Erik Ivins (USA)
Marta Marcos (Spain)
Alvaro Santamaria (France)
Aimée Slangen (Netherlands)
Karen Simon (Netherlands)
Giorgio Spada (Italy)
Guy Woppelmann (France)

Joint Working Group JWG C.5: Understanding the monsoon phenomenon from a geodetic perspective

Affiliation: Commissions 2, 3 & 4, GGOS
Chair: *Balaji Devaraju* (India)
Vice-Chair: *Matthias Weigelt* (Germany)

Introduction

The monsoon phenomenon is one of the large-scale atmospheric circulation processes that drives the water cycle affecting nearly one-third of the global population. It is predominantly acting in the Inter-Tropical Convergence Zone and it controls the agricultural productivity of the countries that fall within this region. Researchers from multiple disciplines have tried to understand and model the monsoon. A century of research efforts has led to a greater understanding of the monsoon phenomenon, but research gaps and open questions remain. Improved understanding will lead to better modelling of the monsoon as well as better forecasting, which will help mitigate some of the potential hazards and risks. Currently, meteorological forecasts on timing and duration of the monsoon, its strength, and its regional distribution are limited. Furthermore, it has been observed that ongoing climate change is linked to and alters the monsoon phenomenon. Many studies point to a weakening of the monsoon, which would mean reduced rainfall to the regions that it feeds. The consequences of such weakening could be disastrous and will threaten food and water security for the region. Therefore, it becomes imperative to observe, monitor and understand the monsoon with every possible means.

The bulk of research on monsoon has been mainly conducted by meteorologists, oceanographers, atmospheric and climate scientists with oceanographic, hydrological and hydrometeorological datasets and modelling. In the recent years, geodetic sensors have been recognized as a very insightful tool for studying climate processes and their spatio-temporal changes. This has been made possible by the increased accuracy and spatial coverage of geodetic sensors, which has enabled detecting the response of the Earth's shape and gravity field to climate-related processes. At the same time geodetic sensors and their data have become integral to Earth system science, and represent critical monitoring tools. Of all geodetic methods satellite altimetry, satellite gravimetry and GNSS positioning have contributed significantly towards understanding sea level change, sea ice change, ice sheet and glacier mass balance, and the hydrological cycle, to name a few. Further, they have opened new pathways in Earth system science including the demand for improved ground networks for calibration. With the advent of satellite-based GNSS reflectometry, geodetic sensors are providing observations of soil moisture and wind speed at unprecedented horizontal scale and temporal resolution.

There is currently a deluge of geodetic sensor data spanning periods of 20 to 100 years, and therefore, perfectly suitable for climate change analysis. It presents a great opportunity to explore the signatures of various environmental and geophysical phenomena. The monsoon is one such phenomenon whose signatures in geodetic sensor data have largely remained underexplored. Some attempts have been made in the past to use geodetic sensor data in monsoon research. For example, satellite altimetry has been used to estimate the geostrophic contribution of monsoon currents. Similarly, precipitable water vapour estimates from continuously observing GNSS stations have been used to study the variations in monsoon precipitation. Nevertheless, the full integration of geodetic sensors data into monsoon modelling has not be achieved yet.

In this context we like to propose a working group to analyse geodetic sensor data in order to identify geodetic variables that are sensitive to the monsoon process, and the signatures that the monsoon leaves in geodetic data. Furthermore, we would like to explore the possibilities of complementing/supplementing monsoon forecast models, and thereby, improve their efficacy. The geodetic sensors to be used include, but are not limited to, satellite altimetry, continuously operating GNSS stations, tide gauges, gravimetric satellites (for example, GRACE, GRACE-FO and SLR), interferometric/polarimetric SAR, and terrestrial gravimeters. We will complement the geodetic sensors with meteorological data, remote sensing data and reanalysis products in global and regional climate models (such as PRECIP, BCC-CSM1.1, ECMWF-SYS4, NCEP-CFS2) to achieve our objectives.

Objectives

- Identify geodetic sensors, and in turn their observables, that are most sensitive to the monsoon phenomenon
- Identify the signatures (amplitudes, scales) of the monsoon phenomenon in geodetic sensor data
- Study the evolution of the monsoon phenomenon in time and space through geodetic sensor data
- Identify limitations and/or the necessity for additional and/or more accurate measurements including in situ networks
- Quantify the sensitivity to error sources, for example, tidal or non-gravitational force modelling
- Compare geodetic sensor data with reanalysis products in global and regional climate models
- Identify the possibility of assimilating geodetic sensor data into monsoon prediction models
- Understand relationships between extreme events and the monsoon phenomenon

Program of Activities

- Participate actively in IAG, AGU, AOGS and EGU conferences and organize sessions
- Organize working group meetings, splinter group meetings at the said symposia
- Collate geodetic sensor data along with their quality information and enable public accessibility via web services
- Conduct dedicated workshops and seminars on monsoon research with focus on geodetic sensor data
- Organize a special issue in a journal or an edited book

Members

Alexander Braun (Canada)
Karim Douch (Germany)
Vagner G. Ferreira (China)
Qiang Chen (Luxembourg)
Subimal Ghosh (India)
Zhizhou Liu (Hong Kong)
Chandrakanta Ojha (USA)
Mohammad Sharifi (Iran)
Alka Singh (USA)
Nico Sneeuw (Germany)
Shivam Tripathi (India)
Bramha Dutt Vishwakarma (UK)
Susanna Werth (USA)
Peng Yuan (Germany)

Joint Working Group JWG C.6: Numerical Simulations for Recovering Climate-Related Mass Transport Signals

Affiliation: Commission 2, GGOS, IGFS
Chair: *Roland Pail* (Germany)
Vice-Chair: *Wei Feng* (China)

Introduction

Gravity field missions are a unique geodetic measuring system to directly observe mass transport processes in the Earth system. Past and current gravity missions such as CHAMP, GRACE, GOCE and GRACE-Follow On have improved our understanding of many mass change processes, such as the global water cycle, ice mass melting of ice sheets and glaciers, changes in ocean mass being closely related to the mass-related component of sea level rise, which are subtle indicators of climate change, on global to regional scale. Next Generation Gravity Missions (NGGMs) expected to be launched in the midterm future have set high anticipations for an enhanced monitoring of mass transport in the Earth system with significantly improved spatial and temporal resolution and accuracy. Science and user needs have been collected and consolidated mainly for the application fields hydrology, cryosphere, ocean and solid Earth, and a corresponding resolution on the need of NGGMs was expressed by IUGG resolution no. 2 adopted in 2015. However, mass transport observations are also very valuable for long-term climate applications. According to GCOS, in general time series of minimum 30 years are needed to decouple natural and anthropogenic forcing mechanisms. Up to now, this hypothesis has never been checked and evaluated for gravity field observations.

Objectives

The main objective of this working group is to set-up and run long-term numerical simulation studies to evaluate the usefulness of gravity field missions for climate-related applications. As a first step, mass transport time series containing long-term changes of climate relevant signals have to be generated in close interaction with climate modelers. They shall then be used for the numerical simulations on the recoverability by means of different NGGM concepts, e.g. GRACE-type in-line single-pair missions, Bender double-pair mission being composed of a polar and an inclined satellite pair, or high-precision high-low tracking missions following the MOBILE concept. In this respect, special emphasis shall be given to the separability of natural and anthropogenic forcing mechanisms in dependence of the length of the measurement time series, the quantification of robustness of derived trends and systematic changes, and the evaluation of their impact to climate modeling.

Program of Activities

The following activities shall be performed:

- Generation of mass transport time series for a time-span of at least 30 years containing climate-relevant signals
- Numerical closed-loop simulations for various mission concepts that are currently in discussion as potential candidates for an NGGM
- Evaluation of recoverability of climate-related signals from these mass transport time series
- Detectability of climate change pathways in the future mass transport time series
- Investigation of separability of natural and anthropogenic forcing processes
- Evaluation of impact for climate model applications towards societal applications
- Evaluation of the detectability of thresholds for early warning

Members

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Qiang Chen (Luxembourg)
Lijing Cheng (China)
Henryk Dobslaw (Germany)
Andreas Groh (Germany)
Martin Horwath (Germany)
Vincent Humphrey (USA)
Erik Ivins (USA)
Laura Jensen (Germany)
Laurent Longuevergne (France)
Ingo Sasgen (Germany)
Bert Wouters (Netherlands)

Joint Working Group JWG C.7: Satellite geodetic data assimilation for hydro-climate research

Affiliation: Commission 2 and GGOS
Chair: *Mehdi Khaki* (Australia)

Introduction

The recent advancements in the space geodetic techniques have gained a lot of attention for improving our understanding of Earth's climate system and its hydrology. Traditionally, various types of models such as hydrologic and atmospheric models have been used for modelling/simulating and predicting hydro-meteorological processes at regional and global scales. Nevertheless, due to various sources of uncertainties such as imperfect modelling, data limitations on both temporal and spatial resolutions, their errors, as well as limited knowledge about empirical model parameters, the accuracy of model simulations can be degraded. Assimilation of satellite geodetic data such as satellite gravimetry, satellite radar and radiometer measurements, synthetic-aperture radar (SAR) and radar interferometry data, and satellite altimetry has been shown to be effective for improving the models' performance and their forecasting skills. This allows us to better study, for example, water resources and their distributions, mass variations and balance, extreme events such as droughts and floods, ice transfer, and help to adapt to long-term environmental challenges posed by climate changes on continental scales.

Data assimilation (DA) facilitates this data integration by constraining the models' simulations based on observations and error associated with them. The method has become more popular with the advent of the space era since scientific observational methods were not limited any more to terrestrial only and offer high spatiotemporal resolution data with global coverage. Specifically, the application of satellite geodetic measurement has been proven to successfully improve various models such as atmospheric and oceanic models, hydrological models and also coupled (e.g., land-atmosphere) systems. For example, the Gravity Recovery And Climate Experiment (GRACE) terrestrial water storage (TWS) data has been used to enhance land surface model performance. Satellite radar altimetry data over the ocean has been used for enhancing oceanic models. Altimetry-derived surface water over land has been recently applied for improved routing as well as rainfall-runoff estimates. Satellite soil moisture, e.g., from Soil Moisture and Ocean Salinity (SMOS) radiometer and Soil Moisture Active Passive (SMAP) has been used for hydrologic DA and more recently for land-atmosphere coupled DA to better study soil moisture feedback to atmospheric components. The use of space geodetic techniques for DA can be further extended with the development of new missions such as NASA's Surface Water and Ocean Topography (SWOT) global surface water, GRACE Follow-on, and Cyclone Global Navigation Satellite System (CYGNSS) soil moisture. Therefore, satellite geodetic DA has a great potential in hydro-climate studies and it requires more concentrations within the geodesy community. The main objective of establishing this working group within IAG is to bring together people with this expertise to share their knowledge, address the current challenges, and draw more attention to the application of geodetic techniques for DA.

Objectives

- To investigate the contributions of space geodetic DA in Earth systems.
- To develop and analyze theoretical and numerical methods for the efficient integration of satellite measurements with models.
- To better analyze model-data uncertainties in satellite DA and their influence on the model's simulations.
- To explore the application of satellite DA for model calibrations
- To investigate the application of new geodetic platforms for DA objectives.

Program of Activities

- To actively participate in geodetic meetings and promote space geodetic DA, and to monitor current progress and identify challenges.
- To share efforts, ideas, and information regarding the working group objectives.
- To organize related sessions at international events.
- To provide opportunities for more collaborations between group members (within the joint working groups) on satellite DA and publishing important findings.
- To create a web page with information relevant to the working group, bibliographic list of publications, and available research opportunities to also share significant DA outcomes with the public.

Members

Joseph Awange (Australia)
Luca Brocca (Italy)
Harrie-Jan Hendricks Franssen (Germany)
Ibrahim Hoteit (Saudi-Arabia)
Jayaluxmi Indu (India)
Gabrielle J. M. De Lannoy (Belgium)
Hamid Moradkhani (USA)
Christian Massari (Italy)
John T. Reager (USA)
Jan Saynisch (Germany)
Ashkan Shokri (Australia)
Natthachet Tangdamrongsub (USA)
Yoshihide Wada (Austria)
Benjamin Zaitchik (USA)

Joint Working Group JWG C.8: Methodology of comparing/validating/testing climate simulations to/with geodetic data

Affiliation: Commission 2, ICCT
Chair: *Jürgen Kusche* (Germany)

Introduction

Climate model simulations provide a unique tool for understanding past and present climates, and projecting future climate under given scenarios. Comparing simulations to observed data is of key importance for understanding uncertainties and systematic errors, attributing causal relations among competing hypotheses, and lending confidence to predictions. One way geodesy contributes to climate sciences is via providing a unique data record for comparing, validating and testing climate model simulations, e.g. with respect to observed sea level change, mass redistribution or water vapor timeseries. However, what is required from geodesy is beyond 'just' providing long and stable data sets, and challenges must be addressed that require revisiting the methodology.

Climate model simulations often consist of large, single- or multi-model ensembles that need to be evaluated as a whole (i.e. not just the ensemble mean which averages out real variability). Model simulations encompass hundreds of dynamically linked variables with increasing spatial and temporal resolution, as e.g. in climate monitoring applications. Simulations are prone to drifts and biases, and climate science is not only interested in 'deterministic' (or mean) outcomes but e.g. in how statistics of extreme events or turbulent phenomena like eddy kinetic energy varies over time. Testing climate models e.g. for the anthropogenic fingerprint requires that such statistics are derived from (geodetic) data, where uncertainties must be assigned that characterize both measurement and sampling errors. This will require that geodetic methods are critically reviewed and new approaches e.g. that deal with large data quantities and ensembles and/or the reconstruction of data gaps, and that capture statistics beyond the mean and RMS be developed. Moreover, as geodetic techniques evolve (and are integrated with non-geodetic observables), new climate observables as e.g. Earth's Energy Budget come into reach and new methods must be developed.

Objectives

- To contribute to the understanding of past, present and future climate via comparing/validating/testing climate models with geodetic data
- To promote and advance the development of rigorous methods across climate science and geodesy
- To safeguard the proper evaluation of the complex geodetic data sets, which are often built from multiple techniques, over overlapping or non-overlapping time periods, in the presence of background model and other analysis technique changes, in the presence of instrumental errors and biases and the intricacies of geodetic reference frames (i.e. develop 'best-practice' examples)
- To facilitate communication of climate scientists and geodesists with respect to methodological issues
- To enable the reanalysis of long geodetic data sets

Program of Activities

- The WG will first seek to stimulate exchange and collaboration across geodesists from different background (atmospheric remote sensing, altimetry, GRACE) and climate scientists.
- It will organize splinter meetings along conferences and promote session proposals e.g. at EGU and AGU conferences.
- It will eventually seek to consolidate the geodesy methodology and disseminate results in form of a white paper / review paper.

Members

Henryk Dobslaw (Germany)
Petra Friedrichs (Germany)
Vincent Humphrey (USA)
Laura Jensen (Germany)
Anna Klos (Poland)
Felix Landerer (USA)
Ben Marzeion (Germany)
Anne Springer (Germany)

Inter-Commission Committee on Marine Geodesy (ICCM)

President: **Yuanxi Yang** (China)
Vice President: **Heidrun Kopp** (Germany)

Terms of Reference

The Inter-Commission Committee on Marine Geodesy (ICCM) was first proposed by the Chinese National Committee to the IAG Executive Committee (EC) in Kobe, Japan in 2017 and then passed at the Sixth/Seven Meetings of the IAG EC, 2018. The Inter-Commission Committee on Marine Geodesy (ICCM) was formally approved and established following the IUGG General Assembly in Montreal, Canada, 2019.

With over seventy percent of the planet's surface and the most important zones of crustal formation and destruction covered by the oceans, monitoring and understanding the oceans and the seafloor is of highest relevance to secure the human sustainable development. The oceans provide enormous biological and mineral resources while at the same time modulate the climate and weather patterns and serve as an important sink for atmospheric carbon. The oceans and seafloor are crucial to the evolution not only of life, but of the Earth system, yet 80% of marine realm remain unexplored [*NOAA*]. The research foci of the discipline *Marine Geodesy* have enormous economic and scientific potential, however, at present large gaps in ocean surveys, seafloor mapping and remote sensing exist which necessitate IAG's immediate attention.

Research contributions to Marine Geodesy have advanced tremendously during the last two decades:

(i) seafloor geodetic networks have been initiated and established by countries or regions including North and Central America, Europe, New Zealand and Japan, and in the near future more coastal countries may start seafloor observatory plans,

(ii) advanced GNSS/acoustic GPS-A techniques have achieved centimeter accuracy in seafloor geodetic positioning, crucial to marine geohazard monitoring, including undersea earthquakes volcanic eruptions, and submarine landslides as well as monitoring of seafloor infrastructure;

(iii) multi-ocean environment monitoring data are available to potentially improve seafloor geodetic positioning or monitoring of steric sea level and circulations, including temperature and salinity profiles of the Array for Real-time Geostrophic Oceanography (Argo), expendable bathythermograph (XBT) data, ocean-bottom pressure (OBP) data and surface and subsurface ocean current observations.

ICCM strongly encourages research to:

(1) develop and implement a precise seafloor reference frame to enhance marine positioning, navigation and timing (PNT) techniques, and promotes international cooperations to bridge scientific research gaps including the component of the international terrestrial reference frame (ITRF) in the coastal and the deep ocean;

(2) enhance frontier research topics on monitoring changes of the ocean and seafloor, such as sea level change, seafloor tectonic motion and seismological events, steric and mass oceanic variations, changes of the surface and subsurface currents, and changes of waves and wind patterns;

(3) refine a series of marine geodetic models, including barotropic and baroclinic ocean tide models, marine geoid models, dynamic topography models, and coastal reference models such as the mean high water (MHW) and the high-water line (HWL); and

(4) improve the accuracy and resolution of the global seafloor topography particularly in the coastal regions by advancing new seafloor geodetic data acquisitions, innovative data processing, and exploring new topography inversion tools.

Objectives

The overall objectives of the ICCM are

- to shorten the gaps between theory and applications in marine geodesy, and to encourage transdisciplinary integration of the contemporary geodetic sensors, including marine geophysical sensors, oceanic sonar and physical oceanography instrumentation;
- to improve the global realization of the International Terrestrial Reference Frame (ITRF) by connecting the seafloor geodetic network component with the ITRF, and to improve current marine geodetic models by including the space, surface and subsurface geodetic observations;
- to encourage development of marine geodetic methodology, especially for the fusion methods of multi-marine geodetic observations;
- to promote international collaborations in regional marine geodetic surveys, and to develop and establish international conventions for marine geodetic data processing, the seafloor reference frame, and other standards.

To achieve these aims, ICCM will interact and collaborate with the IAG Commissions, GGOS and other IAG related entities (services, projects).

ICCM Activities

The anticipated ICCM activities include:

- service as (co-)conveners of geodesy sessions at major conferences such as IAG, EGU, AGU, AOGS, IUGG, etc.
- organization of marine geodesy symposia, and publication of special issues of international journals such as Marine Geodesy, Journal of Geodesy, and Advanced Space Research.
- creation and maintenance of a website for the dissemination of ICCM related information and data products.

Structure

The general structure of Inter-Commission Committees is specified in the IAG By-laws (§17). The Steering Committee includes the president, the vice-president, the past president, one representative appointed by each Commission, and two representatives of the IAG services. The ICCM activities will be structured in study groups. Due to the inter-commission character of the ICCM, these study groups are always joint study groups, affiliated to one or more of the Commissions, GGOS and/or IAG services. The Joint Study Groups will be established during the first period of the ICCM.

Steering Committee

President: *Yuanxi Yang* (China)
Vice President: *Heidrun Kopp* (Germany)

Representatives
Commission 1: *Geoffrey Blewitt* (USA)
Commission 2: *Roland Pail* (Germany)
Commission 3: *Manabu Hashimoto* (Japan)
Commission 4: *Marcelo Santos* (Canada)
GGOS: *Hansjörg Kutterer* (Germany)
IGFS: *Riccardo Barzaghi* (Italy)
IERS: *Jürgen Müller* (Germany)

Members

Ole Baltazar Andersen (Danish)
Rongxing Li (China)
Ian Church (Canada)
Keiichi Tadokoro (Japan)
Pierre Sakic (Germany)
Morelia Urlaub (Germany)
Valérie Ballu (France)
Xiaoli Deng (Australia)
Tianhe Xu (China)
Felipe Nievinski (Brazil)
Shuqiang Xue (China)
Sajad Tabibi (Luxembourg)
Fanlin Yang (China)
Lifeng Bao (China)

IAG Project – Novel Sensors and Quantum Technology for Geodesy (QuGe)

President: **Jürgen Müller**, Germany
Vice President: **Marcelo Santos**, Canada

http://quge.iag-aig.org

Terms of Reference

The novel developments in quantum physics of the previous decade, including new technologies and related measurement concepts, will open up enhanced prospects for satellite geodesy, terrestrial gravity sensing and reference systems. In close collaboration between physics and geodesy, this new IAG project shall exploit the high potential of quantum technology and novel measurement concepts for various innovative applications in geodesy.

Climate change often is reflected in mass variations on Earth. And, many mass change processes in the hydrosphere, geosphere and atmosphere are widely imprinted in gravitational data. However, gravitational data with better spatial-temporal resolution and higher accuracy is required, which can only be achieved by employing innovative quantum technology concepts. Highly stable and accurate reference systems provide the fundamental backbone to monitor the change processes in the Earth system, where clocks will play a central role in the future.

QuGe will serve as a unique platform for developing and evaluating those novel concepts and observation systems, where also further applications, like in exploration and navigation, may benefit. Technology development and space mission requirements have to be linked to geodetic and geophysical modelling in a synergetic way.

Optical ranging between test masses in satellites, atom-interferometric accelerometry and gradiometry, and chronometric levelling with clocks are the needed approaches to overcome the problems of classical concepts in geodesy. With these novel techniques, mass variations on almost all spatial and temporal scales can be observed with unprecedented accuracy and will serve as input for a multitude of applications in geosciences, from the monitoring of smaller groundwater basins and geodynamic effects to the observation of the complex global mass transport processes in the oceans.

The combination of expertise from quantum physics and geodesy in QuGe, integrating engineering skills and fundamental research, serves as an excellent basis to advance the frontiers of gravimetric Earth observation and the realization of reference systems.

Objectives

QuGe will put its focus on three major pillars

1) Atom interferometry for gravimetry on ground and in space (quantum gravimetry) will allow for a comprehensive set of applications, such as fast local gravimetric surveys and exploration, or the observation of gravimetric Earth system processes with high spatial and temporal resolution. In space, atom interferometry will enable accelerometry and inertial sensing in a modernistic way. The use of atom interferometry in hybrid systems with electrostatic accelerometers may allow to cover a wide spectral range for future inertial sensing and navigation. It will benefit satellite navigation, but also serve as a basis for developing the next generation of gradiometer missions (GOCE follow-on).
2) Laser-interferometric ranging between test masses in space with nanometer accuracy belongs to these novel developments as well, where technology developed for gravitational wave detection and successfully tested in the LISA/pathfinder mission is being prepared for geodetic measurements. GRACE-FO already demonstrates this new development. Even more refined concepts, like tracking a swarm of satellites, might be realized within the next years. Optical techniques may also be applied for test mass sensing in future accelerometers, and even combined to next generation gradiometry in space.

3) Frequency comparisons of highly precise optical clocks connected by optical links give access to differences of the gravity potential over long distances (relativistic geodesy). In the future, relativistic geodesy with clocks will be applied for defining and realizing height systems in a new way, locally as well as globally. As further application, clock measurements will provide long-wavelength gravity field information. Moreover, accurate clocks help to improve the accuracy of the International Atomic Time standard TAI. They are important for all space geodetic techniques as well as for the realization of reference systems and their connections. Another application example is the possible use of high-performance clock networks to support GNSS.

In all three research areas, along with the research on measurement systems and techniques, the analysis models have to be put on a sound theoretical basis. This requires dedicated geodetic and relativistic modelling of the various involved gravity field quantities and measurement concepts.

Structure

Working Groups:

WG Q.1: Quantum gravimetry in space and on ground
WG Q.2: Laser interferometry for gravity field missions
WG Q.3: Relativistic geodesy with clocks

Steering Committee

President: *Jürgen Müller* (Germany)
Vice-President: *Marcelo Santos* (Canada)
WG chairs: *see below*
Representatives of the four Commissions:
IAG Comm. 1: *Erricos Pavlis* (USA)
IAG Comm. 2: *Adrian Jäggi* (Switzerland)
IAG Comm. 3: *Federica Migliaccio* (Italy)
IAG Comm. 4: *Suelynn Choy* (Australia)
Representatives of Services:
IGFS: *Sylvain Bonvalot* (France)
GGOS: *Ulrich Schreiber* (Germany)
Members-at-large:
Wenbin Shen (China)
Gabriel Guimarães (Brazil)

Representative of External Bodies

Partly already proposed as members of the WGs. Additional members, e.g., from industry could be *A. Bresson* (ONERA), *S. Seidel* (OHB), *B. Desruelle* (MuQuans) and others.

Working Groups of the Project

The new WGs will closely collaborate with other components of IAG such as

- IAG SC 2.6 "Gravity and Mass Transport in the Earth System" (*Wei Feng*, Wuhan China)
- IAG SC 2.3 "Satellite Gravity Missions" (*Frank Flechtner*, Potsdam, *Matthias Weigelt*, Hannover, Germany)
- IAG Inter-Commission Committee on Geodesy for Climate Research – *Annette Eicker*, *Roland Pail*, Munich, Germany
- Further collaborations, e.g., with ICCT, IERS, WG on IHRF, JWG on IGRF, etc. will be fixed after start.

WG Q.1: Quantum gravimetry in space and on ground

Chair: *Franck Pereira* (France)
Vice-Chair: *Michele van Camp* (Belgium)

Description

On ground, quantum sensors based on matter wave interferometry with cold atoms are very well suited for rapid and very precise gravity sensing. They can be used as registration instruments and as absolute gravimeters with sub-µGal accuracy. Mobile devices are developed for field campaigns and large-scale stationary devices for achieving extreme precision. While the former enable new strategies for local and regional gravity surveys, the latter will provide a new gravity standard in the future.

In space, the long-term stability and low noise level of quantum sensors will allow improving the spatial gravity field models in GOCE-type gradiometer missions. The determination of mass transport processes on Earth at low and medium degrees in GRACE-type missions will benefit from quantum accelerometers providing the measurement of the specific non-conservative forces. In addition, hybrid systems (i.e. a combination of electrostatic and atom-interferometric accelerometers) can cover a wider spectral range which will greatly support navigation and inertial sensing on ground and in space.

The goal of this WG is to elaborate the major benefit and most promising applications of atom interferometry for gravimetry and inertial sensing in space and on ground.

Objectives

- Terrestrial quantum gravimeters and applications scenarios (including airborne and marine instruments)
- (Hybrid) accelerometers for space missions and spacecraft navigation

- Atom interferometric gradiometry
- Elaboration of further applications / space demonstrator (e.g. pathfinder) like atmosphere research, relativity tests, etc.
- Elaboration of synergies between different science topics in a single mission (Earth observation and fundamental physics, navigation and space exploration, several scenarios for Earth observation, e.g. gravimetry, atmospheric research and magnetometry)

Members (preliminary)

R. Pail (TU Munich)
A. Landragin (Syrte Paris)
P. Bouyer (LP2N Bordeaux)
E. Rasel (LUH Hannover
C. Schubert (LUH Hannover)
T. Lévèque (CNES Toulouse)
O. Carraz (ESA)
L. Mondin (ESA)
A. Rülke (BKG Frankfurt)
M. Krutzik (HU Berlin)
F. Migliaccio (Univ. Milano)
M. Reguzzoni (Univ. Milano)

WG Q.2: Laser interferometry for gravity field missions

Chair: *Michael Murböck* (Germany)
Vice-Chair: *Bob Spero* (USA)

Description

GRACE has excellently demonstrated the great potential of inter-satellite tracking to determine time-variable gravitational signals which are related to mass transport processes in the Earth system. Examples are ice mass loss in Greenland and Antarctica, ground water loss in Asia, droughts in USA, quantification of the global water cycle, mass contribution to sea level rise, mass variation due to land uplift in North America and Scandinavia, or mass changes related to earthquakes. To increase the resolution and to extend the time series, GRACE-FO was launched in May 2018 also carrying a Laser Ranging Interferometer (LRI) as demonstrator which is able to approach an accuracy of tens of nm for inter-satellite ranging.

Optical sensing of the motion of test masses in the gravitational field with nanometer accuracy and beyond can be realized in various measurement concepts such as for ranging between satellites like in GRACE-FO or future swarms of satellites. Further concepts apply LRI for sensing single test-mass motion (accelerometry) or multiple test-mass constellations within one satellite (GOCE-type gradiometry).

The overall goal of this WG is to study optical sensing for inter-satellite tracking, accelerometry and gradiometry, and its applications for next generation gravity field missions.

Objectives

- Interferometric Laser Ranging between swarms of satellites
- Accelerometry with optical readout and application scenarios
- Gradiometry with optical readout
- New concepts for future satellite gravity missions

Members (preliminary)

V. Müller (AEI Hannover)
G. Heinzel (AEI Hannover)
J. Kusche (Uni Bonn)
F. Landerer (JPL Pasadena)
D. Wiese (JPL Pasadena)
P. Bender (JILA Boulder)
G. Metris (OCA, France),
Ch. Le Poncin-Lafitte (Syrte Paris)
S. Jin (Shanghai China)
M. Rothacher (ETH Zurich)
B. Spero (JPL Pasadena)
C. Woodruff (JPL Pasadena)
F. Flechtner (GFZ Potsdam)

WG Q.3: Relativistic geodesy with clocks

Chair: *Gerard Petit* (France)
Vice-Chair: *Jakob Flury* (Germany)
Consultant from Physics: *Christian Lisdat*, Braunschweig, Germany

Description

Optical clocks are sensitive to the gravity potential in which they are operated. The comparison of two clocks will reveal a frequency offset from the value expected from side-by-side comparisons that can directly be related to the potential difference between both clocks. The best optical clocks now reach resolutions of 0.1 m^2/s^2, transportable ones about 2 m^2/s^2. They can be achieved already after few hours of averaging.

We will evaluate how this technique can be used to generate unified and long-term stable height networks and reference systems. This will include discussion about the feasibility to realize a datum by reference to a, e.g., space-borne clock with ideally negligible gravitational interference. Future clock networks might also be used as ground-truth for space missions or even to bridge gaps in satellite observations.

Other aspects to be addressed are the application of observed time-variable signals in de-aliasing of satellite observations. In cooperation with the two previous WGs, sensor fusion concepts will be discussed to utilize the different spatial integration characteristics of clocks and the other gravity sensors to disentangle local and extended signal sources.

In summary, the goals of this WG are using clocks measurements for determining differences of physical heights and gravity potential for various geodetic applications.

Objectives

- Clock networks for unification of height systems
- Gravity field recovery on ground
- Application to realize reference systems, including dedicated space clocks
- Further applications (height/potential variations)
- Potential satellite missions for long-wavelength gravity field recovery, including optical links for comparing the space clocks

Members (preliminary)

N. Newbury (NIST Boulder)
A. Ludlow (NIST Boulder)
P. Delva (Syrte Paris)
P. Visser (TU Delft)
H. Margolis (NPL Teddington)
D. Calonico (INRIM, Torino)
C. Lämmerzahl (ZARM Bremen)
W. Shen (Wuhan, China)
U. Schreiber (GO Wettzell)
M. Santos (Uni New Brunswick)
S. Kopeikin (Uni Missouri)
N. Pavlis (NGA, USA)
P. Pottie (Obs de Paris)
S. Merlet (Obs. de Paris/Syrte)
E. Mazurova (MIGAIK, Moscow)
S. Stellmer (Uni Bonn)
J. Kusche (Uni Bonn)
Y. Tanaka (Tokyo Japan)
Hua Guan (WIPM, Wuhan, China)

Communication and Outreach Branch (COB)

President: **Szabolcs Rózsa** (Hungary)
Secretary: **Gyula Tóth** (Hungary)

web: http://www.iag-aig.org

Development

The Communication and Outreach Branch (COB) was created by the IAG Council at its special meeting in Budapest, 7 September 2001. A *Call for Participation* was issued by the IAG Central Bureau (CB) to fill this position.

The offer of the Hungarian Academy of Sciences (HAS)/Budapest University of Technology and Economics (BME) was elected by the Executive Committee (EC) at its meeting in Nice, 11 April, 2003. The IAG Council at the 23rd IUGG/IAG General Assembly (Sapporo, Japan, 30 June-11 July, 2003) has confirmed this election. Thus, the COB started its activities in July 2003, and in the period of 2019-2023 will be the fifth term in the operation of the COB by the BME.

The Communication and Outreach Branch is one of the components of the Association. According to the new Statutes (§5) of the IAG, the COB is the office responsible for the promotional activities of the IAG and the communication with its members.

Terms of Reference

According to §18 of the new By-laws of the IAG:

a) The function of the Communication and Outreach Branch is to provide the Association with communication, educational/public information and outreach links to the membership, to other scientific Associations and to the world as a whole.
b) The responsibilities of the Communication and Outreach Branch shall include the following tasks:
   (i) Promote the recognition and usefulness of geodesy in general and IAG in particular.
   (ii) Publications (newsletters).
   (iii) Membership development.
   (iv) General information service and outreach.
c) The Communication and Outreach Branch shall also assist the IAG General Secretary, in the following tasks as required:
   (i) Maintenance of the IAG website.
   (ii) Setting up Association schools.
   (iii) Setting up meetings and conferences.
d) The IAG Executive Committee establishes the COB on a long-term basis by issuing a Call for Participation. The responding organization(s) and the IAG Executive Committee shall then negotiate the Terms of Reference and other conditions
e) The President of the COB shall be elected by the IAG Council after consideration of a COB proposal.
f) Major decisions related to the operations of the COB shall be made by a Steering Committee consisting of the following voting members:
   (i) Communication and Outreach Branch President.
   (ii) IAG Secretary General.
   (iii) Editor-in-Chief of the Journal of Geodesy.
   (iv) Editor-in-Chief of the IAG Symposia Series.
   (v) Up to 5 other members appointed by the Executive Committee on the recommendation of the President of the Communication and Outreach Branch.

Program of Activities

According to the structure of the IAG, the individual membership has been introduced in addition to the traditional National Members. However, the individual membership requires a more commercial, member-oriented operation of the Association. The main purpose of the COB is to promote communication and interaction among all its members and to facilitate the work of IAG in general. Therefore, the COB is a permanent IAG office for publication, publicity and visibility of the Association.

The planned activities of the COB are split into two main groups:

a) communicational activities, and
b) membership developments and promotional activities which enable the growth of the IAG.

One of the major tasks of the COB is to create the channels of the communication within the Association. Our intention is to maintain a simple, structured way of communication using various information technologies (IT). The *communication of the IAG* is done using the following channels:

- the official IAG website (see the chapter IAG on the Internet in this issue),
- publication of the IAG Newsletters and the Geodesist's Handbook in cooperation with the IAG Office.

The official *IAG website* acts on one hand as the most important interface to the outside community, and on the other hand it is the first pillar of the communication infrastructure of the Association. Therefore, the content of the website is defined to support both roles.

The server operating at the IAG COB, handles *mailing lists,* which is one of the major source of information for the members. The members receive the announcements and Newsletters via e-mail and through the website.

The electronic version of the *IAG Newsletter* is published monthly on the IAG website and is distributed to the members in PDF format via e-mail. A selection of the Newsletter articles is published in the Journal of Geodesy.

COB is active in the *membership developments and promotional activities.* The major channel of the *promotional activities* is the IAG website. Additionally, several brochures and leaflets are available for download and printing, which

- introduce the IAG to the global community,
- emphasize the mission statement of IAG, and
- describe the advantages of being an IAG member.

Our intention is that these brochures should be available at every conference organized and/or sponsored by IAG. Therefore the COB should also represent IAG at all major meeting (including not only IUGG General Assemblies, IAG Scientific Assemblies, AGU and EGS meetings, but also at IAG-sponsored meetings) with different IAG materials (brochures, etc). These brochures are also made available for download from the IAG website (www.iag-aig.org).

Another important task of COB to promote and support the outreach activities of IAG. Our plan is to collect the existing materials supporting primary and high-school education as well as promoting geodesy to students. Moreover, additional syllabus and exercises are to be developed.

Steering Committee

The COB has a Steering Committee (SC) with the following members:
Ex officio voting members:
COB President: *Szabolcs Rózsa* (Hungary)
IAG Secretary General: *Markku Poutanen* (Finland)
Editor-in-Chief of the JoG: *Jürgen Kusche* (Germany)*
Editor-in-Chief of the IAG Symposia Series:
Jeff Freymueller (USA)*

Other voting members:
Gyula Tóth (Hungary), COB Secretary, Editor of the IAG Newsletter
Anne Joergensen (Norway, GGRF)
Hussein Abd-Elmotaal (Egypt)
Nancy Wolfe Kotary (USA)
TBD (South America)
TBD (Asia-Pacific)

*Editors may be substituted by the respective Assistant Editors

Permanent Guests (non-voting):
Zuheir Altamimi (Germany), IAG President
Richard Gross (USA), IAG Vice-President
Harald Schuh (Germany), IAG Immediate-Past President

The COB operates an office the address of which is as follows:

IAG Communication and Outreach Branch
c/o Department of Geodesy and Surveying
Budapest Univ. of Technology and Economics
P.O.Box 91, H-1521 Budapest, Hungary
Phone: +36-1-463 3222/3213, Fax: +36-1-463 3192
E-mail: szrozsa@iag-aig.org / iagcob@iag-aig.org

Global Geodetic Observing System (GGOS)

Chair of the GGOS Coordinating Board: **Basara Miyahara** (Japan)
Vice-Chair of the GGOS Coordinating Board: **Laura Sanchez** (Germany)
Director of the Coordinating Office: **Martin Sehnal** (Austria)

http://www.ggos.org

GGOS Background

Preamble

The proposal for the Global Geodetic Observing System (GGOS) was developed by the GGOS planning group between 2001 and 2003 according to the Bylaws of the International Association of Geodesy (IAG). The proposal was accepted by the IAG Executive Committee and the IAG Council at their meetings during the XXIII IUGG General Assembly in Sapporo in July 2003. GGOS was endorsed by the IUGG through Resolution No. 3 at the same General Assembly.

Changes in the IAG Bylaws in 2007 resulted in GGOS being recognized as an integral component of IAG along with Services and Commissions. This transformed the status of GGOS from that of an IAG Project to an IAG component. Specific to GGOS are IAG Bylaw numbers 1(d) and 15. During 2009-2016, and again in 2017, revisions to the structure of GGOS were discussed leading in 2018 to the Terms of Reference, primarily to update changes to the organizational structure of GGOS.

According to the IAG Bylaws 1(d): *"The Global Geodetic Observing System (GGOS) works with the IAG Services to provide the geodetic expertise and infrastructure necessary for the monitoring of the Earth system and global change research."*

GGOS Vision

Advancing our understanding of the dynamic Earth system by quantifying our planet's changes in space and time.

GGOS Mission

- To provide the observations needed to monitor, map, and understand changes in the Earth's shape, rotation, and mass distribution.
- To provide the global geodetic frame of reference that is the fundamental backbone for measuring and consistently interpreting key global change processes and for many other scientific and societal applications.
- To benefit science and society by providing the foundation upon which advances in Earth and planetary system science and applications are built.

We live on a dynamic planet in constant motion that requires long-term continuous quantification of its changes in a truly stable frame of reference. GGOS and its related research and IAG services will address the relevant science issues related to geodesy and geodynamics in the 21st century, but also issues relevant to society (global risk management, geo-hazards, natural resources, climate change, severe storm forecasting, sea level estimations and ocean forecasting, space weather, and others). It is an ambitious program of a dimension that requires strong cooperation within the geodetic, geodynamic and geophysical communities, and the establishment of strong links to other international organizations. GGOS will provide this integration at the highest level, in service to the technical community and society as a whole.

GGOS Strategic Direction

Overarching Strategic Areas of GGOS

The GGOS Goals, Objectives, and Outcomes are built around four strategic areas that are directly attributable to the established GGOS goals. These areas were established in the 2011 Strategic Plan and continue to be relevant to the activities and future efforts of GGOS in subsequent strategic plans. The strategies are related to each goal but are overarching in nature – just as each goal acts in support of other goals, each strategy has a role in all of the goals.

1. *Geodetic Information and Expertise* (intangible assets). GGOS outcomes will support the development and maintenance of organizational intangible assets, including geodetic information and expertise. The development of this strategic area will benefit all other goals and objectives.
2. *Global Geodetic Infrastructure* (advocacy for, and sustenance of, tangible assets). Development of, advocacy for, and maintenance of existing global geodetic infrastructure is in direct support of each GGOS goal.
3. *Services, Standardization, and Support* (internal and external coordination). Optimal coordination, support, and utilization of IAG services, as well as leveraging existing IAG resources, are critical to the progress of all GGOS goals and objectives.
4. *Communication, Education, and Outreach* (public relations, external education and outreach, internal continuing education and training). Marketing, outreach, and engagement are critical elements for sustaining the organizational fabric of GGOS.

IAG Services, Commissions, and Inter-Commission Committees in Support of GGOS

In order to accomplish its mission and goals, GGOS depends on the IAG Services, Commissions and Inter-Commission Committees. The Services provide the infrastructure and products on which all contributions of GGOS are based. The IAG Commissions and Inter-Commission Committees provide expertise and support for the scientific development within GGOS. In summary, GGOS is IAG's central interface to the scientific community and to society in general.

IAG is a Participating Organization of the Group on Earth Observations (GEO). GGOS acts on behalf of the IAG in GEO and actively contributes to the Global Earth Observation System of Systems (GEOSS).

The GGOS 2020 Book[1] serves as the initial basis for the implementation of GGOS, as the observing system of IAG, and is used to derive work plans based on its recommendations.

GGOS Structure

Overview of Key GGOS Elements

Structural Elements:

The organizational structure of GGOS is comprised of the following key elements which are depicted in Fig. 1:

GGOS Consortium – is the collective voice for all GGOS matters.

GGOS Coordinating Board – is the central oversight and decision-making body of GGOS.

GGOS Executive Committee – serves at the direction of the Coordinating Board to accomplish day-to-day activities of GGOS tasks.

GGOS Science Panel – advises and provides recommendations to the Coordinating Board relating to the scientific content of the GGOS 2020 book and its updates; and represents the geodetic and geoscience community at GGOS meetings.

GGOS Coordinating Office – coordinates the work within GGOS and supports the Chair, the Executive Committee and the Coordinating Board; and coordinates GGOS external relations.

GGOS Bureau of Products and Standards – tracks, reviews, examines, evaluates all actual standards, constants, resolutions and products adopted by IAG or its components and recommends their further use or proposes the necessary updates.

GGOS Bureau of Networks and Observations – develops a strategy to design, integrate and maintain the fundamental geodetic infrastructure including communication and data flow; monitors the status of the networks and advocates for implementation of core and other co-located network sites and improved network performance.

GGOS Affiliates – are national or regional organizations that coordinate geodetic activities in that country or region. GGOS Affiliates allow increased participation in GGOS, especially by organizations in under-represented areas of Africa, Asia-Pacific, and South and Central America.

[1] Global Geodetic Observing System: Meeting the Requirements of a Global Society on a Changing Planet in 2020, *H.-P. Plag* and *M. Pearlman* (editors), Springer, 2009

GGOS Committees, Working Groups and Focus Areas (formerly known as Themes) – address overarching issues common to several or all IAG components, and are a mechanism to bring the various activities of the Services, Commissions and Inter-Commission Committees together, or to link GGOS to external organizations. Focus Areas are cross-disciplinary and address specific focus areas where GGOS contributors work together to address broader and critical issues.

Fundamental Supporting Elements of GGOS

IAG – promotes scientific cooperation and research in geodesy on a global scale and contributes to it through its various research bodies. GGOS is the Observing System of the IAG.

IAG Services, Commissions and Inter-Commission Committees – are the fundamental supporting elements of GGOS. GGOS works with these IAG components to provide the geodetic infrastructure that is necessary for monitoring the Earth system and for global change research. GGOS, built upon the existing IAG Services and their products, will provide a framework for existing or future Services and will strive to ensure their long-term stability.

GGOS Inter-Agency Committee (GIAC) – was a forum that sought to generate a unified voice to communicate with Governments and Intergovernmental organizations (GEO, CEOS, UN bodies) in all matters of global and regional spatial reference frames and geodetic research and applications. GIAC was dissolved when the United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM) Working Group on the Global Geodetic Reference Frame (GGRF) was elevated to the permanent Subcommittee on Geodesy of the UN-GGIM.

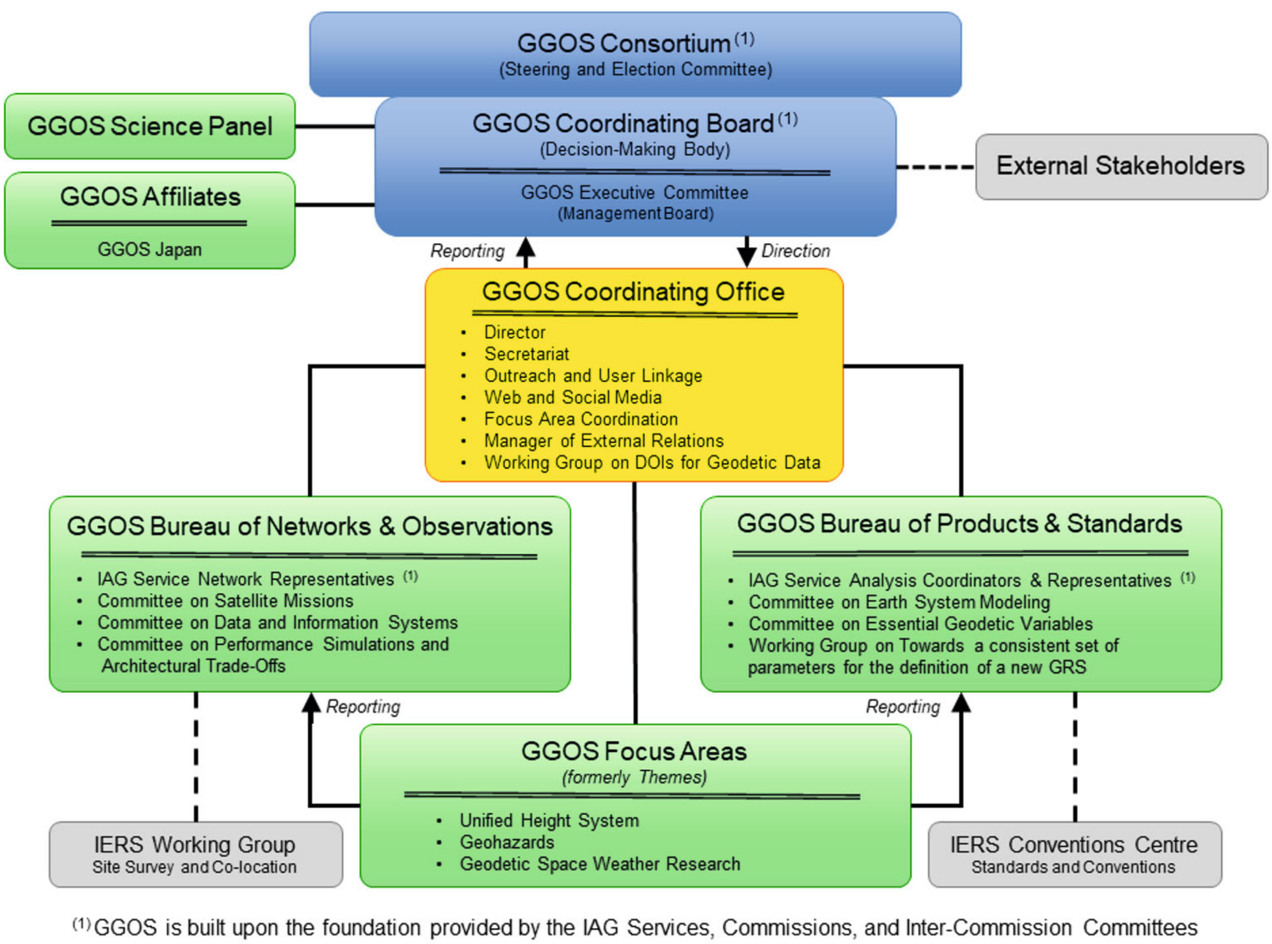

Fig. 1 Organization structure of GGOS (December 2019)

United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM) – led by United Nations Member States, UN-GGIM aims to address global challenges regarding the use of geospatial information and to serve as a body for global policymaking in the field of geospatial information management.

UN-GGIM Subcommittee on Geodesy (SCoG) – provides an intergovernmental forum for cooperation and exchange of dialogue on issues relating to the maintenance, sustainability and enhancement of the Global Geodetic Reference Frame (GGRF).

Details of the Structure of GGOS

GGOS Consortium

The GGOS Consortium is the voice and essentially the large steering committee of GGOS. It reviews GGOS progress and activities and nominates and votes for the candidates for the elected positions on the GGOS Coordinating Board.

The GGOS Consortium is comprised of up to two designated representatives from each IAG Service, Commission, and Inter-Commission Committee and one representative from each GGOS Affiliate. The Chair of an IAG Service Governing or Directing Board, and the Director of the Central Bureau or Coordinating Office, as well as Commission and Inter-Commission Committee Presidents and Vice Presidents and Chairs of GGOS Affiliates may be those designated members. However, no person may represent two or more components, and no one may have more than one vote.

The presiding Chair of GGOS is ex-officio the Chair of the Consortium. GGOS Consortium decisions are based on consensus. Decisions requiring a vote are decided by simple majority of the votes cast. The quorum is met when at least fifty percent of members are present, but electronic voting is acceptable provided a quorum responds.

The Consortium is the nominating and electing body for the GGOS Coordinating Board. The Consortium will meet at least once a year. Observers may participate in meetings of the Consortium at the discretion of the Chair.

GGOS Coordinating Board

The Coordinating Board (CB) is the decision making body of GGOS. Decisions are based upon consensus, whenever possible. Decisions requiring a vote are decided by simple majority of the votes cast. The quorum for a valid vote is participation of fifty percent of the voting members of the Coordinating Board. Votes may be held in person at meetings, or by appropriate electronic means at the discretion of the GGOS Executive Committee. The Coordinating Board will meet at least once yearly, although twice yearly is preferable. Observers may participate in meetings of the Coordinating Board at the discretion of the Chair.

Coordinating Board Members

Voting members:	
GGOS Chair (votes in case of a tie)	1
GGOS Vice-Chair	1
GGOS Science Panel Chair (ex-officio)	1
GGOS Coordinating Office Director (ex-officio)	1
GGOS Manager of External Relations (ex-officio)	1
GGOS Bureau Directors (ex-officio)	2
GGOS Affiliate Representatives (elected by the Consortium)	2
IAG President or designated representative (ex-officio)	1
IAG Service Representatives (elected by the Consortium)	4
IAG Commission and Inter-Commission Committee Representatives (elected by the Consortium)	2
Members-at-Large (elected by the GGOS CB)	3
Total Voting Members	19
Non-voting members:	
GGOS Committee and Working Group Chairs (ex-officio)	6
GGOS Focus Area Leads (ex-officio)	4
GGOS Web and Social Media Manager (ex-officio)	1
Immediate Past Chair of GGOS (ex officio)	1
Total Non-Voting Members	12

Total membership of Coordinating Board
19 Voting Members
12 Non-Voting Members
31 Total members

Chair

The Chair of the GGOS Coordinating Board is determined according to the IAG Bylaws. The Chair of the GGOS Coordinating Board is also known as the GGOS Chair. The GGOS Chair presides over meetings of the GGOS Consortium, Coordinating Board, and Executive Committee. The Chair is the principal spokesperson and representative of GGOS to the IAG and outside organizations.

Vice Chair

The Vice Chair of the GGOS Coordinating Board is elected by the Coordinating Board. The Vice Chair assists the Chair and serves as the Chair in the absence of the Chair or when a motion involving the Chair is being discussed.

Members-at-Large

Members-at-Large are invited to join the Coordinating Board in order to provide balance in representation of geographical regions or unique capabilities. The Chair, with the assistance of the Coordinating Office, appoints an Election Committee to organize the voting process and to ensure availability of the nominated candidates. The Election Committee then presents the final list of Members-at-Large candidates to the CB for a vote.

Appointment of the Chair and Election of Coordinating Board Members

The process for elections to the GGOS Coordinating Board will follow the four-year IAG General Assembly, which takes place during the IUGG General Assembly (see IAG Bylaws for more detail). Candidates nominated to serve on the Coordinating Board as IAG Service, Commission, and Inter-Commission Committee representatives must be members of the GGOS Consortium. Candidates nominated to serve on the Coordinating Board as GGOS Affiliate representatives must be members of the GGOS Affiliates. The CB elects the Vice-Chair of the GGOS CB by a vote. However, the GGOS Chair is elected by the IAG in consultation with the GGOS Coordinating Board.

GGOS Executive Committee

The GGOS Executive Committee (EC) is comprised of the following members:

GGOS Chair	1
GGOS Vice-Chair	1
GGOS Coordinating Office Director	1
GGOS Manager of External Relations	1
GGOS Bureau Directors	2
Voting Members of the CB selected for EC membership	2
Total	**8**

Every other year, the GGOS Chair submits a list of his or her candidates for the two open EC member spaces to the CB for approval. These candidates must be voting members of the CB in order to be nominated to the EC.

The Immediate Past Chair of GGOS, the Chair of the GGOS Science Panel, and the President of IAG or designated representative are all permanently invited guests at meetings of the Executive Committee. Other observers may be invited to attend EC meetings (or teleconferences) as needed.

GGOS Science Panel

The GGOS Science Panel is an independent and multi-disciplinary advisory board that provides scientific support and guidance to the GGOS steering and coordination entities as requested. This support may include organization of relevant scientific sessions at conferences, workshops, and other events.

The IAG Commissions and Inter-Commission Committees each nominate two candidates and the GGOS Focus Areas each nominate one candidate to the Science Panel subject to approval by the CB. The CB may appoint additional Members-at-Large to the Science Panel in order to provide balance in representation of geographical regions or unique capabilities. The immediate past Chair of the Science Panel is a Member of the Science Panel.

The Science Panel will elect its own Chair to be approved by the CB.

IAG Services, Commissions and Inter-Commission Committees

GGOS works with these IAG components to provide the geodetic infrastructure necessary for monitoring the Earth system and global change research. GGOS respects the bylaws and terms of reference for these essential components. GGOS is built on the existing IAG Services and their products. GGOS is not taking over tasks of the existing, and well working IAG Services. GGOS will provide a framework for existing or future Services and strive to ensure their long-term stability.

GGOS Committees, Working Groups and Focus Areas

GGOS Committees and Working Groups (WG) are established by the Coordinating Board as needed. Working Groups are established for one 4-year period, Committees for longer periods of time. The Coordinating Board appoints their Chairs and prepares and approves their charters. The members of Committees and Working Groups are nominated by their Chairs and confirmed by the Coordinating Board.

Focus Areas are cross-disciplinary and are meant to consider gaps and needed future products. The GGOS CB approves the Focus Areas. The CB appoints Focus Area leads. Focus Areas outline their charter and propose plans to address the work that they will undertake.

GGOS Coordinating Office

The GGOS Coordinating Office (CO) performs the day-to-day activities in support of GGOS, the Executive Committee, the Coordinating Board, and the Science Panel, and ensures coordination of the activities of the various components. The CO ensures information flow, maintains documentation of the GGOS activities, and manages specific assistance functions that enhance the coordination across all areas of GGOS, including inter-services coordination and support for workshops. The CO in its long-term coordination role ensures that the GGOS components contribute to GGOS in a consistent and continuous manner. The CO also maintains, manages, and coordinates the GGOS web presence and outreach.

The position of Manager of External Relations resides within the Coordinating Office. The GGOS Manager of External Relations coordinates GGOS engagement with external organizations such as the Group on Earth Observations (GEO), the Committee on Earth Observation Satellites (CEOS), and the International Science Council (ISC) World Data System (WDS). The CB elects the Manager of External Relations by a vote.

Bureau of Products and Standards

The Bureau of Products and Standards keeps track of the strict observations of adopted resolutions, geodetic standards, standardized units, fundamental physical constants and conventions in all official products provided by the geodetic community. It reviews, examines and evaluates all actual standards, constants, resolutions and conventions adopted by ISO, ISC, IUGG, IAU, IAG and its components, and recommends further use or proposes the necessary updates. It identifies eventual gaps in standards and products, and initiates steps to close them with, e.g., resolutions by the IUGG and/or IAG Councils.

Bureau of Networks and Observations

The Bureau of Networks and Observations develops a strategy to design, integrate and maintain the fundamental infrastructure in a sustainable way to satisfy the long-term (10–20 years) requirements identified by the GGOS Science Panel. The Bureau advocates for implementation of core and other co-located network sites to satisfy GGOS requirements, monitors the present state of the networks and projects future status, and supports and encourages infrastructure critical for the development of data products essential to GGOS. Primary emphasis must be on sustaining the infrastructure needed to maintain the evolving global reference frames, while at the same time ensuring the broader support of the scientific applications of the collected data. Coordinating and implementing the GGOS co-located station network is a key focus of the Bureau.

GGOS Affiliates

A GGOS Affiliate is a national or regional organization that coordinates geodetic activities in that country or region. GGOS Affiliates provide a forum for multi-technique, space-geodetic discussions, work to improve the quality of space-geodetic observations, and encourages the different agencies in that country or region that own, operate, and maintain the space-geodetic infrastructure there to collaborate with each other. To become a GGOS Affiliate, interested organizations submit an application to GGOS which is approved by the GGOS CB by a vote.

GGOS Coordinating Board (Voting Members):

GGOS President/Chair: *Basara Miyahara* (Japan)
Vice-President/Chair: *Laura Sánchez* (Germany)
Chair of GGOS Science Panel: *Kosuke Heki* (Japan)
Director of Coordinating Office: *Martin Sehnal* (Austria)
Manager of External Relations: *Allison Craddock* (USA)
Directors of Bureaus of Networks and Observations: *Michael Pearlman* (USA)
Director of Bureau of Products and Standards: *Detlef Angerman* (Germany)
GGOS Japan Affiliate Representatives: *Toshimichi Otsubo* (Japan)
IAG President: *Zuheir Altamimi* (France)
IAG Service Representative: *Riccardo Barzaghi* (Italy)
IAG Service Representative: *Daniela Thaller* (Germany)
IAG Service Representative: *Sean Bruinsma* (France)
IAG Service Representative: *Robert Heinkelmann* (Germany)
IAG Commissions and ICC Representative: *Tonie Van Dam* (Luxemburg)
IAG Commissions and ICC Representative: *Adrian Jäggi* (Switzerland)
Member-at-Large: *María Cristina Pacino* (Argentina)
Member-at-Large: *Nicholas Brown* (Australia)
Member-at-Large: *Ludwig Combrinck* (South Africa)

GGOS Bureau of Networks and Observations

Director: **Michael Pearlman** (USA)

The Bureau of Networks and Observations develops a strategy to design, integrate and maintain the fundamental infrastructure in a sustainable way to satisfy the long-term (10-20 years) requirements identified by the GGOS Science Panel. Primary emphasis must be on sustaining the infrastructure needed to maintain the evolving global reference frames, while at the same time ensuring the broader support of the scientific applications of the collected data. Coordinating and implementing the GGOS co-located station network is a key focus for the Bureau.

GGOS Bureau of Networks & Observations

- IAG Service Network Representatives
- Committee on Performance Simulations and Architectural Trade-offs
- Committee on Data and Information
- Committee on Satellite Missions

Structure

Director: *Michael Pearlman* (USA);
Secretary: *Carey Noll* (USA)
Analysis Representative: *Erricos Pavlis* (USA)

Members:

PLATO Committee: *Daniela Thaller* (Germany)
Benjamin Männel (Germany)

Missions Committee: *Roland Pail* (Germany)
C.K. Shum (USA)

Data and Information: *Nicholas Brown* (Australia)
Carey Noll (USA)

IGFS: *Riccardo Barzaghi* (Italy)
George Vergos (Greece)

IVS: *Hayo Hase* (Germany)
Dirk Behrend (USA)

ILRS: *Toshi Otsubo* (Japan)
Jean-Marie Torre (France)

IGS: *Allison Craddock* (USA)
Gary Johnston (Australia)

IDS: *Jérôme Saunier* (France)
Guilhem Moreaux (France)

Tide Gauges: *Elizabeth Bradshaw* (UK)
Lesley Rickards (UK)

Richard Gross (USA)

In addition, the IERS Working Group on Site Survey and Co-location also participates in the BN&O activities; this Working group is now in the process of reorganization with *Ryan Hippenstiel* / NOAA as Chair.

Objectives

The Bureau of Networks and Observations (BNO) supports the networks capability available to the IAG in its goal to provide geodetic data products of sufficient quantity, quality and temporal and spatial resolution to improve our understanding of the dynamic Earth for both scientific understanding and societal needs. Fundamental to achieving reaching this goal is the maintenance and further development of the globally available terrestrial and celestial reference frames, which are the basis for our metric measurements over space, time, and evolving technology.

The BN&O advocates for implementation of the global space geodesy network of sufficient capability and geographic coverage to achieve data products essential for

GGOS and serves as a coordinating point for the Services to meet, discuss status and plans, and examine common paths for meeting GGOS requirements. Committees and working groups are included in the Bureau in recognition of their synergistic role with Bureau activities.

The role of the BNO is to:

- Advocate for the expansion and upgrade of the space geodesy network for the maintenance and improvement of the reference frame and other GGOS priorities; Main focus will be on the Reference Frame; but the other applications need to be accommodated;
- Encourage partnerships to build and upgrade network infrastructure
- Organize and expand the GGOS affiliated network;
- Monitor network status; projected network evolution based on input from current and expected future participants, estimate performance capability 5 and 10 years ahead;
- Conduct simulation studies and analyses to assess impact on reference frame products of: network configuration, system performance, technique and technology mix, co-location conditions, site ties, and network trade of options (PLATO);
- Develop Metadata Systems for a wide range of users including GGOS; near term strategy for data products (Carey Noll at GSFC) and a more comprehensive longer-term plan for an all-inclusive system (Nick Brown at GA) (Committee on Data and Information);
- Provide the opportunity for representatives from the Services and the Standing Committees to meet and share progress and plans; discuss issues of common interest; meetings at EGU, AGU, GGOS Days, etc.;
- Talks and posters on the Bureau at EGU, AGU, JPGU-AGU, AOGS meetings, etc.;
- Letters/documentation to support stations, current/ new missions, and analysis centers;

Tasks

- Continue recruiting station membership in the GGOS Network through the CfP; issue membership certificates (great response);
- Continue monitoring network status and plans; develop next network projection status for 5 and 10 years ahead;
- Provide next update of the "Guideline for GGOS Core Sites and Co-locations Sites" document;
- Work with the IGFS and IHRF, the PSMSL and the other services to integrate relevant parameters from other ground networks (gravity field, tide gauges, etc.) into the GGOS network to support GGOS requirements including the reference frame, a unified height system, etc.; advocate for installation of GNSS receivers at appropriate tide gauges; Global Geodetic Observing System (GGOS)
- Support the technique Services on the promotion of recommended technologies/configurations and procedures in the establishment of new sites and the upgrading of current sites, and in the evaluation of performance of new stations and new capabilities after they become operational;
- Continue simulation and trade-off studies for network options (PLATO Committee)
- Continue metadata systems development; target phase 1 (data products) for 2020 (Committee on Data and Information)
- Improve communication and information exchange and coordination with the space missions; (Committee on Satellite Missions)
- Work with the IERS Working Group on Site Survey and Co-location to improve the quality of site ties and instrument reference points:
- Continue BNO meetings to meet, discuss status and plans, and examine common interests and requirements;
- Continue presentation at international meetings in BNO activities and plans;
- Continue providing letters and documentation support
- Update the Bureau web pages for public use (to be compatible with the new GGOS website in process;

Committees of the Bureau of Networks and Observations

BNO C1: Committee on Performance Simulations and Architectural Trade-Offs

(joint with IAG Sub-Commission 1.1)

Chair: *Daniela Thaller* (Germany)
Vice-Chair: *Benjamin Maennel* (Germany)

Objective

The PLATO Committee / Working Group has currently 12-member groups working on simulations and data analysis covering the full range of existing ground and space assets, including VLBI, SLR, GNSS, and DORIS. The main focus is on how do we use existing observation capabilities (stations, observation concepts, tracking performance, etc.) including co-location in space with existing and new dedicated satellites to best support GGOS planning and implementation.

Project future network capability and examine trade-off options for station deployment and closure, technology upgrades, the impact of site ties, additional space missions, etc. to maximize the utility of the GGOS assets:

- Use simulation techniques to assess the impact on reference frame products of network configuration, system performance, technique and technology mix, colocation conditions, site ties, space ties (added spacecraft, etc.), analysis and modeling techniques, etc.;
- Use and developing improved analysis methods for reference frame products by including all existing data and available co-locations (i.e., include all satellites and use all data types on all satellites);
- Make recommendations on network configuration and strategies based on the simulation and trade-off studies.

Investigations that are being included in the PLATO activity include studying the impact of:

- The full range of existing ground and space assets:
  - GNSS assets (ground and space)
  - SLR (beyond Lageos-1 and -2) including ranging to GNSS satellites;
  - LLR assets
  - VLBI assets including tracking of GNSS satellites;
  - Co-located assets in space (e.g. GRACE, OSTM/Jason-2)
  - Mixture of existing legacy stations and simulated next generation stations
  - Improved GNSS antenna calibrations and clock estimation strategies (GNSS alone or when in combination with SLR, VLBI, and DORIS)
- Anticipated improved performance of current systems:
  - Simulate the impact of upgrading existing stations and their procedures
  - Simulate the impact of additional ground surveys at colocation sites (site ties)
- Potential future space assets: - Co-locate all four techniques in space on a dedicated satellite

Tasks

- Examining trade-off options for station deployment and closure, technology upgrades, the impact of site ties, etc. and project future network capability based on network configuration projected by the BNO or relevant IAG services (IGS, ILRS, IVS, IDS);
- Investigating the impact of improved SLR tracking scenarios including spherical satellites, LEOs, and GNSS satellites and VLBI satellite tracking on reference frame products;
- Identifying technique systematics by analyzing short baselines, data from new observation concepts, and available co-locations (e.g., consistent processing of LEO and ground-based observations);
- Investigating the best-practice methods for co-location in space and assessing the impact of co-location in space on reference frame products based on existing satellites and by simulation studies for proposed missions.

BNO C2: Committee on Data and Information

Chair: *Nicholas Brown* (Austria)
Vice-Chair: *Carey Noll* (USA)

Objectives

The Committee on Data and Information had two GGOS objective areas:

- Development and implementation of a portal;
- Development and implementation of a metadata scheme

Initial work on the portal was done by *Bernd Richter*. When he retired, the task was transferred to the GGOS Coordinating Office.

Near term Metadata activity (Carey Noll/CDDIS)

CDDIS is implementing collection-level metadata through the Earth Observation System Data and Information System (EOSDIS) Common Metadata Repository (CMR). CDDIS is an EOSDIS Distributed Active Archive Centers (DAACs) and thus utilizes the EOSDIS infrastructure to manage collection and granule level metadata describing CDDIS archive holdings; these metadata include DOIs associated with the CDDIS archive contents. The CMR is accessible through APIs and can be used in the future by GGOS to find geodetic data and products available through the CDDIS.

Longer-Term Metadata activity (Nick Brown / Geoscience Australia)

Development of a Geodesy Markup Language (GeodesyML), for the GNSS community; potential for expansion to the other space geodesy techniques and GGOS. The current study is identifying metadata standards and requirements, assessing critical gaps and the how these might be filled, what changes are needed in the current standards, and who are the key people who should work on it (more comprehensive scheme). The schema that would be used by its elements for standardized metadata communication, archiving, and retrieval. First applications would be the automated distribution of up-to-date station configuration and operational information, data archives and catalogues, and procedures and central bureau communication. One particular plan of great interest is a site metadata schema underway within the IGS Data Center Working Group. This work is being done in collaboration with the IGS, UNAVCO, SIO, CDDIS, and other GNSS data centers. The current activity is toward a means of exchange of IGS site log metadata utilizing machine-to-machine methods, such as XML and web services, but it is expected that this will be expanded to the other Services to help manage site related metadata and to other data related products and information. Schema for the metadata should follow international standards, like ISO 19xxx or DIF, but should be extendable for technique-specific information, which would then be accessible through the GGOS Portal.

Tasks:

Activities underway at CDDIS:

1. Complete collection level metadata related to CDDIS data and product holdings in the EOSDIS Common Metadata Repository (CMR)
2. Re-ingest CDDIS data holdings in order to extract granule level metadata linked to new collection level records

Activities underway in Geodesy Markup Language (GeodesyML) System

1. Review and document the metadata and standards requirements of precise positioning users in expected high use sectors (e.g. precision agriculture, intelligent transport, marine, location-based services etc.).
2. Assess and document the critical gaps in standards which restrict how Findable Accessible Interoperable and Reusable (FAIR) precise positioning data is for the expected high use sectors.
3. Record use cases of standards being applied well and the benefits it provides to users.
4. Review the "use cases" of geodetic data developed by Geoscience Australia and the IGS Data Center Working Group and document what work and time would be required to ensure these use cases can be met in international standards. This could be:
   - Identify which gaps can be filled by GeodesyML
   - Identify which components of GeodesyML would be better, handled by / integrated with, existing standards (such as TimeSeriesML, SensorML, Observations and Measurements) where possible.
   - Identify which components of already existing international geospatial infrastructure can be approached (such as the European Inspire initiative)
   - Advise on who we should engage with from the OGC/ISO community to facilitate a change to a standard to meet our requirements.
5. Work with Project Partners to develop and test other use cases (e.g. integration of geodetic data with geophysics data (e.g. tilt meters), Intelligent Transport Sector data, mobile applications). Then, document what work and time would be required to ensure these use cases can be met in international standards.
6. Provide advice on how to best engage with the right communities to learn from their experiences, test their tools and influence the development of required standards.

BNO C3: Committee on Satellite Missions

Chair: *Roland Pail* (Germany)
Vice-Chair: *C.K. Shum* (USA)

Objectives

Improve coordination and information exchange with the missions for better ground-based network response to mission requirements and space-segment adequacy for the realization of GGOS goals

- Advocate, coordinate, and exchange information with satellite missions as part of the GGOS space infrastructure, for a better ground-based network response to mission requirements and space-segment adequacy for the realization of the GGOS goals.
- Assess current and near-future satellite infrastructure and their compliance with GGOS 2020 goals;
- Support proposals for new mission concepts and advocate for needed missions;
- Interfacing and outreach with other components of the Bureau; especially the ground networks component, the simulation activity (PLATO), as well as the Bureau of Standards and Products.

Tasks

- Continue the regular activities, i.e. updating the two central lists, supporting future satellite missions, etc.
- Work with the Coordinating Office to set up and maintain a Satellite Missions Committee section on the GGOS website;
- Evaluate the contribution of current and near-term satellite missions to the GGOS 2020 goals;
- Work with GGOS Executive Committee, Focus Areas, and data product development activities (e.g., ITRF) to advocate for new missions to support GGOS goals;
- Support the Executive Committee and the Science Committee in the GGOS Interface with space agencies;
- Finalize and publish (outreach) of Science and User Requirements Document for future gravity field missions.
- Increase the exchange and collaboration with PLATO; set up a more formal procedure of collaboration; discuss needs and run simulations to study the impact of future satellite missions, identify gaps for fulfilling the GGOS goals, etc.

GGOS Bureau of Products and Standards

Director: **Detlef Angermann** (Germany)
Vice-Director: **Thomas Gruber** (Germany)

Members:

M. Gerstl (Germany)
R. Heinkelmann (Germany)
U. Hugentobler (Germany)
L. Sánchez (Germany)
P. Steigenberger (Germany)

Associated Members, Representatives of IAG Services and other entities involved:

R. Barzaghi (Italy)	*K. Kelly* (USA)
S. Bonvalot (France)	*J. Kusche* (Germany)
H. Capdeville (France)	*F. Lemoine* (USA)
M. Craymer (Canada)	*J.M. Lemoine* (France)
J. Gipson (USA)	*E. Pavlis* (USA)
T. Herring (USA)	*M. Reguzzoni* (USA)
J. Hilton (USA)	*J. Ries* (USA)
L. Hothem (USA)	*N. Stamatakos* (USA)
E. Ince (Germany)	*H. Wziontek* (Germany)

GGOS components associated to the BPS:

- Committee Earth System Modelling (Chair: *M. Thomas*)
- Committee Essential Geodetic Variables (Chair: *R. Gross*)
- BPS Working Group Towards a consistent set of parameters for the definition of a new GRS (Chair: *U. Marti*)

Objectives

- The Bureau of Products and Standards (BPS) supports GGOS in its goal to obtain consistent products describing the geometry, rotation and gravity field of the Earth. A key objective of the BPS is to keep track of adopted geodetic standards and conventions across all IAG components as a fundamental basis for the generation of consistent geometric and gravimetric products. The work is primarily build on the IAG Service activities in the field of data analysis and combinations. The BPS shall act as contact and coordinating point regarding homogenization of standards and IAG products. Moreover the BPS interacts with external stakeholders that are involved in standards and conventions, such as the International Organization for Standardization (ISO), the Committee on Data for Science and Technology (CODATA), the International Astronomical Union (IAU) and the UN GGIM Subcommittee on Geodesy (SCoG). The objectives of the BPS may be divided into two major topics/activities:

1. Standards: This includes the compilation of an inventory regarding standards, constants, resolutions and conventions adopted by IAG and its components and a regular update of such a document. The BPS has compiled an inventory "*GGOS Bureau of Products and Standards: Inventory of Standards and Conventions used for the Generation of IAG Products*" (see IAG Geodesist's Handbook 2016). This inventory provides an assessment of the present status, identifies gaps and shortcomings concerning the generation of the IAG products, as well as recommendations. This inventory needs to be regularly updated since the IAG standards and products are evolving over time. Finally, the BPS shall propose the adoption of new standards where necessary and propagate standards and conventions to the wider scientific community and promote their use. In this context, the BPS recommends the development of a new Geodetic Reference System GRS20XX based on the best estimates of the major parameters related to a geocentric level ellipsoid.
2. Products: The BPS shall take over a coordinating role regarding the homogenization of standards and geodetic products. The present status regarding IAG Service products shall be evaluated, including analysis

and combination procedures, accuracy assessment with respect to GGOS requirements, documentation and IAG metadata information for IAG products. The Bureau shall initiate steps to identify user needs and requirements for geodetic products and shall contribute to develop new and integrated products. The BPS shall also contribute to the development of the GGOS Portal (as central access point for geodetic products), to ensure interoperability with IAG Service data products and external portals (e.g., GEO, EOSDIS, EPOS, GFZ Data Services).

Tasks

- The tasks of the Bureau of Products and Standards are to:
- act as contact & coordinating point for homogenization of IAG standards and products
- keep track of adopted geodetic standards and conventions across all IAG components, and initiate steps to close gaps and deficiencies
- interact with external stakeholders in the field of standards and conventions (e.g., IAU, ISO, BIPM, CODATA, UN-GGIM, …), the BPS director has been nominated as IAG representative to ISO/TC 211 and as IAG representative in the UN-GGIM GGRF Working Group "Data Sharing and Development of Geodetic Standards"
- update the inventory on standards and conventions used for the generation of IAG products
- contribute to the re-writing/revising of the IERS Conventions, the BPS director has been nominated as Chapter Expert for Chapter 1 "General definitions and numerical standards"
- focus on the integration of geometric and gravimetric observations and to support the development of integrated products (e.g., GGRF, IHRF, atmosphere products)
- contribute to the UN GGIM Subcommittee on Geodesy (SCoG)
- contribute to the Committee on Essential Geodetic Variables (EGVs)
- contribute to the GGOS DOI Working Group

Committees and Working Groups of the Bureau of Products and Standards

GGOS Committee on Earth System Modeling

Chair: *Maik Thomas* (Germany)

The GGOS Committee on "Earth System Modeling" tends to promote the development of physically consistent modular Earth system modeling tools that are simultaneously applicable to all geodetic parameter types (i.e., Earth rotation, gravity field and surface geometry) and observation techniques. Hereby, the committee contributes to:

- the interpretation of geodetic monitoring data and, thus, to a deeper understanding of dynamical and complex interacting processes in the Earth system responsible for the observed variations;
- the establishment of a link between the geodetic products delivered by GGOS and numerical process models;
- a consistent combination and integration of observed geodetic parameters derived from various monitoring systems and techniques;
- the utilization of geodetic products for the interdisciplinary scientific community.

Objectives

The overall long-term goal is the development of a physically consistent modular numerical Earth system model for homogeneous processing, interpretation and prediction of geodetic parameters with interfaces allowing the introduction of constraints provided by geodetic time series of global surface processes, rotation parameters and gravity variations. This ultimate goal implicates the following objectives:

- development of Earth system model components considering interactions and relationships between surface deformation, Earth rotation and gravity field variations as well as interactions and physical fluxes between relevant compartments of the Earth system;
- promotion of homogeneous processing of geodetic monitoring data (de-aliasing, reduction) by process modeling to improve analyses of geodetic parameter sets;
- contributions to the interpretation of geodetic parameters derived from different observation techniques by developing strategies to separate underlying physical processes;
- contributions to the integration of geodetic observations based on different techniques in order to promote

validation and consistency tests of various geodetic products.

Activities

Major current activities focus on:

- the implementation of generalized modules for the realistic consideration of interactions of near-surface fluids with the geosphere arising, e.g., from surface-loading and self-attraction;
- implementation of interfaces to geodetic monitoring data based on Kalman and particle filter approaches in order to constrain and improve stand-alone model approaches and to prove consistency of various geodetic monitoring products;
- feasibility studies for the provision of error and uncertainty estimates of model predictions of geodetic parameters (Earth rotation, gravity field, surface deformation) due to imperfect model physics, initialization, and external forcing.

Important in-progress activities and future efforts focus on:

- evaluation of opportunities to constrain dynamically coupled model systems with geodetic data products by applying Kalman filter and inversion techniques;
- application of forward modeling and inversion methods in order to improve model-based predictions of geodetic quantities and to invert geodetic observations for the underlying causative processes.

Committee on Essential Geodetic Variables

Chair: *Richard Gross* (USA)

The GGOS BPS Committee on Essential Geodetic Variables was established in 2018 in order to define a list of Essential Geodetic Variables and to assign requirements to them. Essential Geodetic Variables (EGVs) are observed variables that are crucial (essential) to characterizing the geodetic properties of the Earth and that are key to sustainable geodetic observations. Examples of EGVs might be the positions of reference objects (ground stations, radio sources), Earth orientation parameters, ground- and space-based gravity measurements, etc. Once a list of EGVs has been determined, requirements can be assigned to them. Examples of requirements might be accuracy, spatial and temporal resolution, latency, etc. These requirements on the EGVs can then be used to assign requirements to EGV-dependent products like the terrestrial and celestial reference frames. The EGV requirements can also be used to derive requirements on the observing systems that are used to observe the EGVs. And the list of EGVs can serve as the basis for a gap analysis to identify observations needed to fully characterize the geodetic properties of the Earth. During GGOS Days 2017 it was agreed that a Committee within the GGOS Bureau of Products and Standards should be established in order to define the list of Essential Geodetic Variables and to assign requirements to them. This Committee was subsequently established in 2018 and consists of representatives of the IAG Services, Commissions, Inter-Commission Committees, and GGOS Focus Areas.

Tasks

The tasks of the Committee on Essential Geodetic Variables are to:

- Develop criteria for choosing from the set of all geodetic variables those that are considered essential
- Develop a scheme for classifying EGVs
- Within each class, define a list of EGVs
- Assign requirements to each EGV
- Document each EGV including its requirements, techniques by which it is observed, and point-of-contact for further information about the EGV
- Perform a gap analysis to identify potential new EGVs
- Define a list of geodetic products that depend on each EGV
- Assign requirements to the EGV-dependent products
- Hold workshops to engage the geodetic community in the process of defining EGVs, determining their dependent products, and assigning requirements to them

GGOS Working Group: Towards a consistent set of parameters for the definition of a new GRS

Chair: *Urs Marti* (Switzerland)

Terms of Reference

The Geodetic Reference System 1980 GRS80 is still the conventional system for most applications in Geodesy and other Earth sciences. It was defined through the four parameters a (semi-major axis), J2 (Dynamical Form Factor), GM (geocentric Gravitational Constant) and ω (Angular Rotation Velocity). It represents the scientific status of the 1970ies and in its concept, the tidal systems and relativistic theories are not considered. Since its adaptation, various inconsistencies have been introduced into geodetic standards and applications, such as new values for GM or a in the IERS conventions. In 2015, a conventional value for the gravitational potential at sea level W_0 was adopted in an IAG resolution, which is in contradiction to the definition of GRS80.

This WG will publish a new set of defining parameters for a modern GRS based on todays knowledge and calculate all the necessary derived parameters in a consistent way. It will study the necessity to work towards an IAG resolution to replace GRS80 as the conventional system and provide transformation procedures between the two systems. It will study as well the necessity to define and adopt a conventional global gravity field model for standard applications in geodesy, navigation and related topics.

This JWG is assigned to the GGOS Bureau of Products and Standards (BPS) and works together with representatives of IAG Commissions 1 and 2, the Inter-Commission-Committee on Theory (ICCT), the International Gravity Field Service (IGFS), the International Earth Rotation and Reference Systems Service (IERS) and the Committee on Essential Geodetic Variables (EGV).

This JWG will focus its activities on the coordination of the geometric reference frame, the global height system, the global gravity network and their temporal changes. The application of Earth orientation parameters and tidal models and the underlying standard and reference models has to be brought into consistency.

Objectives and activities

The main objectives and activities of this working group are:

- Calculate consistent parameters of a new mean Earth ellipsoid and derived quantities
- Study the necessity to replace the global reference system GRS80 as the conventional system
- Advance the realization of a conventional global reference gravity field model (combined and satellite only)
- Assist the working group for establishing the International Height Reference System (IHRS) in the realization
- Integrating and combining the global gravity network with other techniques
- Study the influence of earth orientation parameters, tidal models and relativistic effects on the realization of a consistent global reference frame in geometry, height and gravity
- Foster the free exchange of geodetic data and products

Members

Urs Marti (Switzerland), Chair
Detlef Angermann (Germany), Chair of GGOS BPS, IERS
Richard Gross (USA) IAG Vice President, Committee on EGV
Ilya Oshchepkov (Russia), GRS, Gravity Networks and Height Systems
Christopher Kotsakis (Greece), Commission 1
Jonas Ågren (Sweden), Commission 2
Ulrich Meyer (Switzerland) COST-G
Riccardo Barzaghi (Italy), IGFS
Jaakko Mäkinen (Finland), Tidal Systems
Pavel Novak (Czech Republic), ICCT
Laura Sánchez (Germany), IHRF
Hartmut Wziontek (Germany), IGRF
John Nolton (USA), GRS
Robert Heinkelmann (Germany), IAU
Sergei Kopeikin (USA), relativistic effects
Erricos Pavlis (USA), ILRS

Focus Area: Unified Height System

Chair: *Laura Sánchez* (Germany)

The present objective of Focus Area Unified Height System is the implementation of the IAG resolution for the definition and realization of an *International Height Reference System* (IHRS) issued during the 2015 IUGG General Assembly. This resolution outlines the conventions for the definition of the IHRS in terms of potential parameters: The definition is given in terms of potential parameters: the vertical coordinates are geopotential numbers ($-\Delta W_P = C_P = W_0 - W_P$) referring to an equipotential surface of the Earth's gravity field realized by the conventional value $W_0 = 62\ 636\ 853.4\ m^2s^{-2}$. The spatial reference of the position P for the potential $W_P = W(\mathbf{X})$ is given by coordinates $\mathbf{X}$ of the International Terrestrial Reference Frame (ITRF). This Resolution also states that the IHRS coordinates should be related to the mean-tide system/mean crust.

At present, a main challenge is the realization of the IHRS; i.e., the establishment of the International Height Reference Frame (IHRF). It is expected that the IHRF follows the same structure as the ITRF: a global network with regional and national densifications, whose geopotential numbers referring to the global IHRS are known. According to the GGOS objectives, the desired accuracy of these global geopotential numbers is $1 \times 10^{-2}\ m^2s^{-2}$. In practice, the precise realization of the IHRS is limited by different aspects; for instance, there are no unified standards for the determination of the potential values W_P, the gravity field modelling and the estimation of the position vectors $\mathbf{X}$ follow different conventions, the geodetic infrastructure is not homogeneously distributed globally, etc. Therefore, the achievable accuracy may be restricted to $10 \times 10^{-2}\ m^2s^{-2} \dots 100 \times 10^{-2}\ m^2s^{-2}$, which is one or two orders of magnitude lower than the desired accuracy.

During the term 2015 – 2019, important advances were achieved: a global core reference network for the IHRF was defined and, within the Colorado experiment, it was possible to compare different methodologies for the determination of the reference coordinates W_P. The results are very promising and these activities will be continued in term 2019 – 2023 by the Joint Working Group (JWG) 0.1.3 "Implementation of the International Reference Frame – IHRF". This working group is a joint initiative of Joint Working Group (JWG) of the GGOS Focus Area Unified Height System, the International Gravity Field Service (IGFS), the IAG Inter-commission Committee on Theory (ICCT) and the IAG Commissions 2 (Gravity field) and 1 (Reference Frames). The corresponding terms of reference are describe in the following.

Joint Working Group 0.1.3: Implementation of the International Height Reference Frame (IHRF)

Chair: *Laura Sánchez* (Germany), Lead of the GGOS Focus Area Unified Height System
Vice-chair: *Riccardo Barzaghi* (Italy), Chair of the International Gravity Field Service

Major objectives of the JWG 0.1.3 are:

- Based on the Colorado experiment outcomes, to elaborate a document with detailed standards and conventions for the realization and maintenance of the IHRS.
- To compute a first static solution for the IHRF core network, to evaluate the achievable accuracy under the present conditions (data availability, computation methods, etc.) and to identify key actions to improve the determination of the IHRS/IHRF coordinates.
- With the support of the IAG Commission 2, the IGFS and the ICCT to promote the study of
- quality assessment in the determination of potential values,
- determination of potential changes with time $\dot{W}$,
- realization of the IHRS in marine areas.
- In agreement with the IGFS and the IAG Commission 2, to design a strategy to install an operational infrastructure within the IGFS to ensure the maintenance and availability of the IHRF in a long-term basis. Aspects to be considered are
  - Updates of the IHRS definition and realization according to future improvements in geodetic theory and observations.
  - Regular updates of the IHRF (e.g. IHRFyyyy) according to new stations, coordinate changes with time, improvements in the estimation of reference coordinates and modelling of the Earth's gravity field, etc.
  - Support in the realisation and utilisation of the IHRS/IHRF at regional and national level.
  - To guarantee an organizational and operational infrastructure to ensure the sustainability of the IHRF.

A strong joint work is planned with

- International Gravity Field Service – IGFS, chair: *R, Barzaghi* (Italy), vice-chair: *G. Vergos* (Greece).
- ICCT JSG: Geoid/quasi-geoid modelling for realization of the geopotential height datum, chairs: *J Huang* (Canada), *YM Wang* (USA).
- IAG SC 2.2: Methodology for geoid and physical height systems, chair: *G. Vergos* (Greece).

- IAG Commission 2.2 WG: Error assessment of the 1 cm geoid experiment, chairs: *M Willberg* (Germany), T Jiang (China).
- IAG Commission 2 JWG: On the realization of the International Gravity Reference Frame, chairs: *H. Wziontek* (Germany), *S. Bonvalot* (France)
- GGOS-BPS WG: Towards a consistent set of parameters for a new GRS, chair *U Martí* (Switzerland).

Members

H.A. Abd-Elmotaal (Egypt)	*M. Varga* (Croatia)
J. Ågren (Sweden)	*G. Vergos* (Greece)
H. Denker (Germany)	*M. Véronneau* (Canada)
W. Featherstone (Australia)	*Y. Wang* (USA)
R. Forsberg (Denmark)	*M. Willberg* (Germany)
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P. Novák (Czech Republic)	*R. Pail* (Germany)
I. Oshchepkov (Russia)	*D. Roman* (USA)
M. Sideris (Canada)	*C. Tocho* (Argentina)
D. Smith (USA)	*H. Wziontek* (Germany)

Focus Area: Geohazards

Chair: *J. LaBrecque* (USA)

The Geohazards Monitoring Focus Area of the Global Geodetic Observing System (GGOS) seeks to apply geodetic science and technology in support of global and regional resiliency to environmental hazards.

The GGOS and its associated IAG services (International GNSS Service (IGS), International VLBI Service for Geodesy and Astrometry (IVS), International DORIS Service (IDS), International Laser Ranging Service (ILRS), International Earth Rotation and Reference Systems Service (IERS), and International Gravity Field Service (IGFS)) provide products that serve as the fundamental geodetic references for science, governments, and industry. The most notable of these products serve as the basic reference for positioning and timing information associated with the Global Navigation Satellite Systems (GNSS) including the International Terrestrial Reference Frame (ITRF), precision orbit and time information and continuing scientific and technical advancements to the utilization of the GNSS data.

These and other GGOS products achieved wide global recognition and acceptance because of their accuracy, timeliness, and continuing technical improvements. These are the very qualities needed for effective environmental warning. In some cases, the acceptance of geodetic applications have been immediate and widespread such as the application of GNSS to understanding and modeling earthquake faults.

However, in other cases geodetic technology has advanced faster than nations can utilize this new capability. The Geohazards Focus Area seeks to accelerate and guide the acceptance of new geodetic capability to improve resilience to environmental hazards. The Focus Area will establish working groups comprised of GGOS members and the responsible agencies of participating nations. The Focus Area encourages the sharing of intellectual, financial and physical resources as recommended by the UN-GGIM (http://ggim.un.org).

As its first initiative, the Geohazards Monitoring Focus Area has issued a Call for Participation (CfP: to research scientists, geodetic research groups and national agencies in support of the implementation of the IUGG 2015 Resolution 4: Global Navigation Satellite System (GNSS) Augmentation to Tsunami Early Warning Systems https://office.iag-aig.org/iag-and-iugg-resolutions. The CfP responders comprise a working group to be a catalyst and a motivating force through the definition of requirements, identification of resources, and the encouragement of international cooperation in the establishment, advancement, and utilization of GNSS for Tsunami Early Warning. The initiative is initially focused upon the Indo-Pacific region following the IUGG 2015 Resolution 4.

Present Status and Progress:

- The Geohazards Focus Area (GFA) is focused upon the implementation of the IUGG 2015 General Assembly Resolution #4. The GFA summarized its previous activities in a 2015 to 2019 quadrennial report to the IAG.
  (https://www.dropbox.com/s/9ivbaqju798y2f9/IAG-Geohazards%20Report%202015-2019.pdf?dl=0).
- Since the establishment of GATEW working group, the working group has grown to 18 members from 12 nations (chart) with the recent inclusion of the Indian National Centre for Ocean Information (INCOIS). As listed in the attached membership chart.

GGOS Working Group on GNSS Augmentation for Tsunami Warning

12 nations - 18 organizations

Country	Organization	Resources	Contact	Email
Australia	GeoScience Australia	Large National Real Time GNSS Network	John Dawson	John.Dawson@ga.gov.au
Chile	U.Chile, Department of Geophysics, CSN	Large National Real time Geodetic and Seismic Network	Sergio Barrientos, Sebastián Riquelme, Juan Baez	sbarrien@dgf.uchile.cl, sebastian@dgf.uchile.cl,jcbaez@csn.uchile.cl
China	GNSS Research Center, Wuhan University	First Real Time Asian Analysis Center	Jianghui Geng	jgeng@whu.edu.cn
China	Shanghai Observatory	Eminent geodetic research organization with strong experience in geodetic infrastructure, analysis and applications.	Shuanggen Jin	sgjin@shao.ac.cn
Colombia	Geological Survey Colombia	Large Real Time GNSS Network, Regional Data Sharing with Brazil, Peru, Panama, Venezuela, COCONet Data Center	Hector Mora	hmora@sgc.gov.co
France	Institut de Physique du Globe de Paris	Strong research in tsunami coupled ionospheric waves and tracking	Giovanni Occhipinti	ninto.a.paris@gmail.com
Germany	GeoForschung Zentrum, Department Geoservices	Strong research and development of GNSS Early Warning including Indonesia and Oman projects	Harald Shuh, Jörn Lauterjung	schuh@gfz-potsdam.de, lau@gfz-potsdam.de
India	Indian National Centre for Ocean Information Services (INCOIS)	INCOIS operates Tsunami Warning Center ESSO and a large array of seismic, tidal guages buoy, GNSS and strong motion accelerometers at sites including the Andaman and Nicobar Islands.	Mrs. Vijaya Sunanda Manneela	shenoi@incois.gov.in, sunanda@incois.gov.in
Italy	University of Rome Geodesy and Geomatics	Initiating research in GNSS Tsunami Warning	Mattia Crespi, Augusto Mazzoni	mattia.crespi@uniroma1.it , augusto.mazzoni@uniroma1.it
Mexico	Instituto de Geofisica, UNAM	Large National GNSS network and analysis system, COCONet Data Center	Enrique Cabral	ecabral@geofisica.unam.mx
New Zealand	GNS Science	Large National Network	Elisabetta D'Anastasion	E.DAnastasio@gns.cri.nz
New Zealand	Land Information New Zealand	Large National Network	Dion Hansen	DHansen@linz.govt.nz
Sri Lanka	Survey Department of Sri Lanka	Strong interest in developing Tsunami Early Warning	P. Sangakkara,Mr A. Dissanayeke	sangakkara@yahoo.com, addsgc@survey.gov.lk
USA	Georgia Tech	Significant focus on subduction zone activity and the generation of tsunamis	Andrew V. Newman	anewman@gatech.edu
USA	Jet Propulsion Laboratory	Real time expertise, Ionospheric mapping, global and operations, earthquake and tsunami warning	Attila Komjathy	attila.komjathy@jpl.nasa.gov
USA	UNAVCO	Global GNSS networks, real time data systems, Global GNSS support	Linda Rowan	rowan@unavco.org
USA	READI Working Group	NASA-NOAA working group developing GNSS Based Tsunami Warning	Yehuda Bock, Timothy Melbourne	ybock@ucsd.edu, tim@Geology.cwu.edu
USA	NASA	NASA Solid Earth Science. Provides funding from GNSS Tsunami Warning development. Cooperating with NOAA in this effort.	Gerald Bawden	gerald.w.bawden@nasa.gov

- The GATEW worked with other organizations to publish a report on GTEWS 2017 in the UNDRR GAR19 report in May 2019 https://www.prevention-web.net/ publications/view/66779. The GAR 19 paper reports on the deliberations and recommendations of the GTEWS 2017 workshop that GGOS GFA cosponsored. The GAR 19 white paper articulates the role of GTEWS technology and the GTEWS 2017 recommendations in the implementation of the Sendai Framework.
- The strong participation exemplified by the GATEW membership now serves as the basis of a GEO community activity Geodesy4Sendai. See page 92 of the GAR19 report of the GTEWS 2017 workshop https://www.earthobservations.org/documents/gwp20_22/gwp2020_summary_document.pdf.
- The Geodesy4Sendai activity raises the recommendation of the GTEWS 2017 workshop to ministerial level discussions.

Planned Actions and Milestones

- 2020 election of a Chair for the GATEW working group/
- Establish the GNSS Shield Consortium as recommended by the GTEWS 2017 workshop.
- Organize the GATEW activities to align with the GEO Geodesy4Sendai community activity
- GTEWS 2020: The GFA is engaged with partnering organization in the planning and fund raising is underway for GTEWS 2020 workshop with a focus upon implementation of the GTEWS 2017 workshop.

Develop Support for GNSS Consortium:

- A proposal to be re-submitted to the US National Science Foundation by members of the READI Group (a member of the GATEW working group) is viewed as a US contribution to GNSS Shield Consortium as recommended by the GTEWS 2017 workshop. Similar efforts by other GATEW is solicited.
- G. Occhipinti (IPGP, France) and M. Crespi (Sapienza University of Rome, Italy) are preparing a proposal to the European Commission to apply ionospheric imaging to the estimation of earthquake and tsunami risk and their resulting disasters.
- If they are successful, these efforts by the European and US membership will be the first contributions to the implementation of the GTEWS 2017 recommendations. Please review the recommendations of the GTEWS 2017 and consider how you might support these recommendations.

Future working groups of the Geohazards Monitoring Focus Area will support compelling initiatives that improve the resiliency of global and regional societies through the application of geodetic science and technology. The working groups mandate will be to develop an attainable and valuable goal as recommended by the GGOS Science panel. Each working group will define a work-plan with an estimated time line that will be subject to periodic review by the GGOS Coordinating Board.

Focus Area on Geodetic Space Weather Research

Chair: *Michael Schmidt* (Germany)

Space weather means today an own, very up-to-date and interdisciplinary field of research. It describes physical processes in space mainly caused by the Sun's radiation of energy. The manifestations of space weather are multiple, for instance, the variations of the Earth's magnetic field or the changing states of the upper atmosphere, in particular the ionosphere and the thermosphere.

The most extreme known space weather event happened at September 1, 1859 – the Carrington storm. Other prominent recent, but much weaker events have been the Halloween storm at October 28 – 30, 2003, or the St. Patrick's storm at March 17, 2015. The strength of these events, their impacts on modern society and the possibility of much stronger future events have brought several countries such as US, UK, Japan, Canada and China to recognize the necessity of studying these impacts scientifically, of developing protection strategies and procedures and to establish space weather data centres and space weather services. As a consequence of these activities the Focus Area on Geodetic Space Weather Research (FA GSWR) was initiated and finally implemented into the GGOS structure. The following statements summarize the necessity of geodesy to deal with the topic space weather: Geodesy has

- to deal with the ionosphere, since the measurements of most of the space-geodetic observation techniques are depending on the properties of the ionosphere along the ray path of an electro-magnetic wave between transmitter and receiver,
- to deal with the thermosphere, since the thermospheric drag is the most important deceleration effect on Low-Earth Orbiting (LEO) satellites below 1000 km and objects in the re-entry stage,
- a long history and large experience in developing and using sophisticated analysis techniques and modelling approaches.

To put the aforementioned issues in a nutshell, the *main objectives* of the FA GSWR are (1) the improvement of positioning and navigation (PPP), (2) the improvement of precise orbit determination (POD) and (3) the study of the coupled processes between magnetosphere, ionosphere and thermosphere (MIT),

Objective (1) aims at the high-precision and the high-resolution (spatial and temporal) modelling of the electron density. This allows to compute a signal propagation delay, which will be used in many geodetic applications, in particular in positioning, navigation and timing (PNT). Moreover, it is also important for other techniques using electromagnetic waves, such as satellite- or radio-communications. Concerning objective (2), satellite geodesy will obviously benefit when working on POD, but there are further technical matters like collision analysis or re-entry calculation, which will become more reliable when using high-precision and high-resolution thermospheric drag models. Objective (3) links the magnetosphere with the first two objectives by introducing physical laws and principles such as continuity, energy and momentum equations and solving partial differential equations.

For a long time geodesists looked at the atmosphere just as a disturbing factor whose impacts on electromagnetic signal propagation, i.e. the signal delay and the bending of the ray path, have to be corrected by applying atmospheric correction models of sufficient accuracy. On the other hand, as already mentioned before, the observation data of various geodetic measurement techniques that are influenced by the atmosphere in different ways provide valuable information on state and dynamics of the ionosphere. These are of great interest also for other disciplines such as meteorology. Today, for Geodetic Space Weather Research geodesy has to go another step forward by introducing physics. To be more specific, we have to take into account the complete chain of cause and effect. This means the research has (1) to start with processes and events on the Sun, (2) to be continued with the effects on the magnetosphere, the ionosphere, the thermosphere and their coupling processes down to the Earth's surface and finally (3) to end by the consideration of the impact of space weather on (geodetic) applications and measurement systems.

Geodetic Space Weather Research is fundamental research, particularly when intending to detect and to survey structures of the ionosphere, e.g. bubbles, or when studying special phenomena like electro-jets. Summarizing, geodetic space weather research has to be based on (a) the use and combination of all space geodetic observation methods, (b) the use of Sun (solar) observations, (c) real-time modelling, (d) the development of deterministic and stochastic forecast approaches and (e) assimilation strategies.

Planned activities of the FA GSWR

- extensive simulation studies which have to be performed in order to assess the impact of space weather on technical systems and to define – as a consequence – necessary actions in case of severe space weather events,
- the development of ionosphere and thermosphere models as stated above as GGOS products for direct application,
- the establishment of recommendations for applications of the models, e.g. in satellite orbit determination, collision analysis and re-entry computations,
- updates of the models as needed and based on the future improvements of modelling strategies, observing systems, etc., and
- the establishment of roadmaps for improving the models by including future satellite measurement systems and missions such as the Formosat-7/COSMIC-2 mission.

To arrive at the above described aims of the FA GSWR one new Joint Study Groups (JSG) and three Joint Working Groups (JWG) have to be installed. In detail, these groups are titled as

- JSG 1: Coupling processes between magnetosphere, thermosphere and ionosphere (implemented at IAG ICCT and joint with GGOS, Focus Area on Geodetic Space Weather Research and IAG Commission 4, Sub-commission 4.3)
- JWG 1: Electron density modelling (joint with IAG Commission 4, Sub-commission 4.3)
- JWG 2: Improvement of thermosphere models (joint w. IAG Commission 4, Sub-commission 4.3 and ICCC)
- JWG 3: Improved understanding of space weather events and their monitoring by satellite missions (joint with IAG Commission 4, Sub-commission 4.3);

For more details see the terms of Reference (ToR) and the descriptions of the JSG and the JWGs presented below. There will be a strong connection and cooperation between the four groups. Since the first is covering the coupling processes, i.e. it has to be dealt with many physical problems, we will install it as JSG at the IAG ICCT.

Other implemented IAG Study Groups (SG) and Working Groups (WG) within the IAG programme will provide valuable input for the FA GSWR, in particular from the Commission 4, Sub-commission 4.3. Finally, it should be mentioned that the work within the FA GSWR will be carried out in close relation to the International Association of Geomagnetism and Aeronomy (IAGA), since this organisation is also concerned with the understanding of properties related, e.g. to the ionosphere and magnetosphere as well as the Sun and the solar wind. Partly, the work will be related to the International Association of Meteorology and Atmospheric Sciences (IAMAS), too.

Overview on one Joint Study Group (JSG) and three Joint Working Groups (JWG):

The running time of these groups is not restricted to the 4-year IAG-period from 2019 to 2023, but could last significantly longer.

JSG 1: Coupling processes between magnetosphere, thermosphere and ionosphere

Implemented at IAG ICCT; joint with GGOS, Focus Area on Geodetic Space Weather Research and Commission 4, Sub-Commission 4.3

Chair: *Andres Calabia Aibar* (China, andres@calabia.com)
Vice-Chair: vacant

Terms of Reference (ToR) / Description:

Consequences of upper-atmosphere conditions on human activity underscore the necessity to better understand and predict the effects of Magnetosphere-Ionosphere-Thermosphere (MIT) processes and coupling, and prevent from potential detrimental effects on orbiting, aerial, and ground-based technologies. For instance, major concerns include the perturbation of electromagnetic signals passing through the ionosphere for accurate and secure use of Global Navigation Systems (GNSS), and the lack of accurate aerodynamic-drag models required for accurate tracking, decay, and re-entry calculations of Low Earth Orbit (LEO) objects, including manned and unmanned artificial satellites. In addition, ground power grids and electronics of satellites could be influenced, e.g., by the magnetic field generated by sudden changes in the current system due to solar storms. Figure1 illustrates the proposed new structure of the Focus Area on Geodetic Space Weather Research (FA GSWR) as a double tetrahedron.

Monitoring and predicting the Earth's upper atmosphere processes driven by solar activity is highly relevant to science, industry and defence. These communities emphasize the need to increment the research efforts for better understanding of the MIT responses to highly variable solar conditions, as well as detrimental space weather effects on our life and society. On the one hand, the electron-density variation produces the perturbation in speed and direction of electromagnetic signals propagated through the ionosphere, and reflects as a time-delay in the arrival of the modulated components from which pseudo-range measurements of Global Navigation Satellite Systems are made, and an advance in the phases of the signal's carrier waves which affects carrier-phase measurements. On the other hand, aerodynamic-drag associated with neutral-density fluctuations resulting from upper atmospheric expansion/contraction in response to variable solar and geomagnetic activity, increases drag and decelerates Low Earth Orbits, dwindling lifespan of space-assets, and making tracking difficult.

Through the interrelations, dependencies, and coupling patterns between ionosphere, thermosphere, and magnetosphere variability, the JSG 1 aims to improve the understanding of the coupled processes in the MIT system, and considerations of the solar contribution. In addition, tides from the lower atmosphere forcing can feed into the electrodynamics, and have a composition effect leading to changes in the MIT system. In this scheme, our tasks are addressed to exploit the knowledge of the tight MIT coupling by investigating multiple types of magnetosphere, ionosphere, and thermosphere observations. The final outcome will help to enhance the predictive capability of empirical and physics-based models through interrelations, dependencies, and coupled patterns of variability between the essential geodetic variables.

Objectives:

- Characterize and parameterize the global modes of MIT variations associated with diurnal, seasonal, and space weather drivers, as well as the lower atmosphere forcing.
- Determine and parameterize the mechanisms responsible for discrepancies between observables and the present models.
- Detect and investigate coupled processes in the MIT system for the deciphering of physical laws and principles such as continuity, energy and momentum equations and solving partial differential equations.

Members:

1. *Piyush M. Metha* (Department of Aerospace Engineering and Mechanics, University of Minnesota, USA, piyushmukeshmehta@gmail.com)
2. *Liang Yuan* (Shanghai Astronomical Observatory, Chinese Academy of Sciences, China, llyuan@shao.ac.cn)
3. *Astrid Maute* (National Center for Atmospheric Research, High Altitude Observatory, Colorado, USA, maute@ucar.edu
4. *Gang Lu* (High Altitude Observatory, National Center for Atmospheric, ganglu@ucar.edu)
5. TBC

JWG 1: Electron density modelling

Joint with Commission 4, Sub-Commission 4.3

Chair: *Fabricio dos Santos Prol* (Germany) Fabricio.Dos-SantosProl@dlr.de
Vice-Chair: *Alberto Garcia-Rigo* (Spain) garciar-igo@ieec.cat

Terms of Reference (ToR)/Description:

The main goal of this group is to disseminate and evaluate established methods of 3-D electron density estimation in terms of electron density, peak height, Total Electron Content (TEC), or other derived products that can be effectively used for GNSS positioning or for analyzing perturbed conditions due to representative space weather events. It is planned to generate products, showing the general error given by such 3-D electron density estimations and, also, distribute information regarding to space weather conditions. To achieve this main goal, the following objectives are defined.

Objectives:

- Develop a database, where the methods from the group members will be able to be evaluated in terms of GNSS, radio-occultation, DORIS, in-situ data, altimeters, among other electron density and TEC measurements.
- Evaluate established methods for 3-D electron density estimation in order to define their accuracy related to specific parameters of great importance for Space Weather and Geodesy.
- Generate products indicating the space weather conditions and expected errors of the methods.
- Carry out surveys in order to detect if the products are linked to the user's specific needs. Based on an analysis of the user needs, re-adaptations will be identified in order to improve the products in an iterative process. It is planned to define which parameters are of interest for the users and to detect additional information that may be required.

Members:

1. *Andreas Goss* (Technical University of Munich, Germany, andreas.goss@tum.de)
2. *Bruno Nava* (ICTP, Italy, bnava@ictp.it)
3. *David Themens* (University of New Brunswick, Canada, david.themens@gmail.com)
4. *Feza Arikan* (Hacettepe University, Turkey, arikan@hacettepe.edu.tr)
5. *Gopi Seemala* (Indian Institute of Geomagnetism, India, GopiSeemala@iigs.iigm.res.in)
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9. *Mainul Hoque* (German Aerospace Center, Germany, Mainul.Hoque@dlr.de)
10. *Marcio Muella* (Universidade do Vale do Paraíba, Brazil, Brazil, mmuella@univap.br)
11. *Michael Schmidt* (Technical University of Munich, Germany, mg.schmidt@tum.de)
12. *Mir-Reza Razin* (Arak University of Technology, Iran, mr.ghafari@arakut.ac.ir)
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18. *Yenca Migoya-Orue* (ICTP, Italy, yenca@ictp.it)

JWG 2: Improvement of thermosphere models

Joint with IAG Commission 4, Sub-Commission 4.3 and ICCC

Chair: *Christian Siemes* (The Netherlands) C.Siemes@tudelft.nl
Vice-Chair: *Kristin Vielberg* (Germany) vielberg@geod.uni-bonn.de)

Terms of Reference (ToR) / Description:

Mass density, temperature, composition and winds are important state parameters of the thermosphere that affect drag and lift forces on satellites. Since these significantly influence the orbits of space objects flying at altitudes below 700 km, accurate knowledge of the state of the thermosphere is important for applications such as orbit prediction, collision avoidance, evolution of space debris, and mission lifetime predictions. Drag and lift forces can be inferred from space geodetic observations of accelerometers, which complement other positioning techniques such as GNSS, satellite laser ranging or radar tracking of space objects. The objective of the working group is to improve thermosphere models through providing relevant space geodetic observations and increasing consistency between datasets by advancing processing methods. Broadening the observational data basis with geodetic space observations, which are available now for a time span of 20 years, will also benefit climatological studies of the thermosphere.

Objectives:

- Review space geodetic observations and state-of-the-art processing methods
- Advance processing methods to increase consistency between observational datasets
- Improve thermosphere models through providing accurate and consistent space geodetic observations
- Study the impact of improved observational datasets and advanced processing methods on orbit determination and prediction
- Use of improved thermosphere models and observational data sets to forward the investigation of thermosphere variations in the context of climate change

Members:

1. *Michael Schmidt* (Technical University of Munich, Germany, mg.schmidt@tum.de)
2. *Armin Corbin* (University of Bonn, Germany, corbin@geod.uni-bonn.de)
3. *Ehsan Forootan* (Cardiff University, UK, ForootanE@cardiff.ac.uk)
4. *Mona Kosary* (University of Tehran, Iran, mona.kosary@ut.ac.ir)
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JWG 3: Improved understanding of space weather events and their monitoring by satellite missions

Joint with IAG Commission 4, Sub-Commission 4.3

Chair: *Alberto Garcia-Rigo* (Spain) garciarigo@ieec.cat
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Terms of Reference (ToR) / Description:

Space weather events cause ionospheric disturbances that can be detected and monitored thanks to estimates of the vertical total electron content (VTEC) and the electron density (Ne) of the ionosphere. Various space geodetic observation techniques, in particular GNSS, satellite altimetry, DORIS, radio occultations (RO) and VLBI are capable of determining such ionospheric key parameters. For the monitoring of space weather events, low latency data availability is of great importance, ideally real time, to enable triggering alerts. At present, however, only GNSS is suited for this task. The use of the other techniques is still limited due latencies of hours (altimetry) or even days (RO, DORIS, VLBI).

The JWG 3 will investigate different approaches to monitor space weather events using the data from different space geodetic techniques and, in particular, combinations thereof. Simulations will be beneficial to identify the contribution of different techniques and prepare for the analysis of real data. Different strategies for the combination of data will be investigated.

Furthermore, the geodetic measurements of the ionospheric parameters will be complemented by direct observations of the solar corona, where solar storms originate, as well as of the interplanetary medium. Spacecrafts like SOHO or ACE have monitored the solar corona and the solar wind for decades and will be beneficial, together with data from other spacecrafts like SDO, in assessing the performance of geodetic observations of space weather events. Data from Parker Solar Probe, which will allow even greater insights, has just recently been made publicly available.

Geodetic VLBI is also capable of measuring the electron density of the solar corona when observing targets angularly close to the Sun and will be useful for comparisons. Other solar-related satellite missions such as Stereo, DSCOVR, GOES, etc. provide valuable information such as solar radiation, particle precipitation and magnetic field variations. Other indications for solar activity - such as the F10.7 index on solar radio flux, SOLERA as EUV proxy or rate of Global Electron Content (dGEC), will also be investigated. The combination and joint evaluation of these data sets with the measurements of space geodetic observation techniques is still a great challenge. Through these investigations, we will gain a better understanding of space weather events and their effect on Earth's atmosphere and near-Earth environment.

Objectives

- Selection of a set of historical representative space weather events to be analysed.
- Determination of key parameters and products affected by the selected space weather events.
- Identification of the main parameters to improve real time determination and the prediction of ionospheric/plasmaspheric VTEC and Ne estimates as well as ionospheric perturbations in case of extreme solar weather conditions.
- Improving the (near) real time determination of the electron density within the ionosphere and plasmasphere to detect space weather events.
- Combination of measurements and estimates derived from space geodetic observation techniques by conducting extensive simulations, combining different data sets and testing different algorithms.
- Comparison and validation using external data, in particular data from spacecraft dedicated to monitoring the solar corona.
- Interpretation of the results. Correlate acquired data/products with space weather events' impact on geodetic applications (e.g. GNSS positioning, EGNOS performance degradation).

Members:

TBD

GGOS Bureau of Products and Standards

Inventory of Standards and Conventions used for the Generation of IAG Products

D. Angermann[1] · **T. Gruber**[2] · **M. Gerstl**[1] · **R. Heinkelmann**[3] · **U. Hugentobler**[2] · **L. Sánchez**[1] · **P. Steigenberger**[4]

Contents

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Preface and scope of the document

The GGOS Bureau of Products and Standards (BPS), formerly known as Bureau for Standards and Conventions (BSC), has been established as a component of the Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) in 2009. The BPS supports GGOS in its goal to obtain geodetic products of highest accuracy and consistency. In order to fully benefit from the ongoing technological improvements of the observing systems, it is essential that the analysis of the precise space geodetic observations is based on the definition and application of common standards and conventions and a consistent representation and parameterisation of the relevant quantities. This is of crucial importance for the establishment of highly accurate and consistent geodetic reference frames, as the basis for a reliable monitoring of the time-varying shape, rotation and gravity field of the Earth. The BPS also concentrates on the integration of geometric and gravimetric parameters and the development of new products, required to address important geophysical questions and societal needs.

A key objective of the BPS is to keep track and to foster homogenisation of adopted geodetic standards and conventions across all components of the IAG as a fundamental basis for the generation of consistent geometric and gravimetric products. The work is primarily build on the IAG Service activities in the field of data analysis and combinations. The BPS acts as contact and coordinating point regarding homogenisation of standards and IAG products. Towards reaching these goals, the BPS has compiled an inventory of standards and conventions currently adopted and used by the IAG and its components for the processing of geometric and gravimetric observations as the basis for the generation of IAG products. The first version of such an inventory has been released in January 15, 2016 and published in the Geodesists Handbook 2016 (Angermann et al. 2016; Drewes et al. 2016).

Since 2016, a remarkable progress has been achieved in the field of standards and conventions as well as concerning the data analysis and generation of geodetic products, which will be reported in an updated version of this document. During the last four years, new realisations of the terrestrial and celestial reference systems, the ITRF2014 and ICRF3, as well as an updated series for the Earth Orientation Parameters (EOP 14 C04) were generated by the Product Centers of the International Earth Rotation and Reference Systems Service (IERS). In this time period also the modelling and data analysis of the contributing space techniques Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Global Navigation Satellite Systems (GNSS), Doppler Orbit Determination and Radiopositioning Integrated by Satellite (DORIS) have been significantly enhanced due to the efforts of the technique-specific IAG Services. Furthermore, a significant progress has been achieved in the field of gravity-related products provided by the gravimetric IAG Services as well as regarding the realisation of the International Height Reference Frame (IHRF). Data analysis issues that are common to all the space geodetic techniques are discussed at the Unified Analysis Workshops, which are co-organised by GGOS and the IERS. This updated version of the inventory also reflects the outcome of the two latest Workshops held in Paris in 2017 and 2019.

In this updated version of the inventory the general structure of the original document is largely kept, whereas the contents of the individual sections has been updated to take into account the latest developments. Some (unchanged) parts of the original version are also part of this updated version to ensure the readability as a “stand-alone” document. A summary of the updates is provided in the Document Change Record (see Table 1). This second version of the BPS inventory reflects the status of January 31, 2020.

The scope of this document is summarised as follows: Chapter 1 provides in the first section some general information about GGOS including its mission, goals and the organisational structure. The second part of this introductory chap-

Table 1: Document change record summarizing the major changes of the document.

Version/Date	Comments / Summary of Changes
1.0 2016-01-15	First version of the document Angermann D., Gruber T., Gerstl M., Heinkelmann R., Hugentobler U., Sánchez L., Steigenberger P.: GGOS Bureau of Products and Standards: Inventory of standards and conventions used for the generation of IAG products. In: Drewes H., Kuglitsch F., Adám J. (Eds.) The Geodesist’s Handbook 2016. Journal of Geodesy, 90(10), 1095–1156, 10.1007/s00190-016-0948-z, 2016
2.0 2020-01-31	Updated Version, prepared for publication in The Geodesist’s Handbook 2020 **Preface** updated. **Chapter 1.1** : IAG/GGOS structure updated, Fig. 1.2 updated. **Chapter 1.2** : Update of Standards and Conventions (e.g., ISO, CODATA, IUGG, IAG and IAU Resolutions), issues on IERS Conventions (e.g., re-writing/revising IERS Conventions) updated. **Chapter 2** : Update of BPS description and organisational structure. **Chapter 3** : Updates on numerical standards, outcome of GGOS/IERS Unified Analysis Workshops 2017 and 2019 incorporated, recommendations on numerical standards updated. **Chapter 4** : Updates of product-based review (see below). **Chapter 4.1** : Summary on ICRF2 (sect. 4.1.2) moved to section 4.1.3.1 “History of ICRS realisations”, new section 4.1.3.2 on ICRF3 included, other sections of 4.1 updated, recommendations updated. **Chapter 4.2** : New section 4.2.2 “History of ITRS realisations” included, former chapter on ITRF2008 shortened and moved to 4.2.2, new section on ITRF2014 (4.2.3) included, other sections of 4.2 updated, outcome of Unified Analysis Workshops incorporated, recommendations updated. **Chapter 4.3** : Section 4.3.2 updated (e.g., IERS EOP 08 C04 replaced by IERS EOP 14 C04), other sections of 4.3 updated, outcome of Unified Analysis Workshops incorporated, recommendations updated. **Chapter 4.4** : Updates on GNSS satellite orbits (e.g., satellite property information, satellite orbit models) and recommendations. **Chapter 4.5** : The chapter on gravity and geoid has been revised to incorporate the developments and the progress with the IGFS during the last four years, in this updated version also new and more specific recommendations are provided. **Chapter 4.6** : This chapter has been revised to incorporate the developments and the progress in the field of height systems and their realisations during the last four years, the recommendations have been revised. **Chapter 5** : A few minor updates have been performed in the summary. **Bibliography** : The references have been updated.

ter deals with standards and conventions from a general view along with some relevant nomenclature, and it presents current standards, standardised units, fundamental physical standards, resolutions and conventions that are relevant for geodesy. In the second chapter the mission and goals of the BPS are summarised, along with a description of its major tasks. It also presents the BPS staff and the associated members, representing the IAG Services, the International Astronomical Union (IAU) and other entities involved in standards and conventions. Chapter 3 focusses on numerical standards, including time and tide systems and it gives recommendations for future improvements. Chapter 4 is the key element of this document and it contains the product-based review, addressing the following topics: Celestial reference systems and frames, terrestrial reference systems and frames, EOP, GNSS satellite orbits, gravity and geoid, as well as height systems and their realisations. In this product-based inventory, the BPS presents the current status, identifies gaps and inconsistencies as well as interactions between different products. In this context also open problems and recommendations regarding standards and conventions for the generation of IAG products are provided. Finally, a summary and an outlook towards future developments is provided.

Acknowledgements

The original version of this BPS inventory (published in 2016) has been reviewed in a two step procedure. In the first step an (internal) review initiated by the BPS has been performed, followed by a second review cycle which was conducted under the responsibilty of the IAG Bureau (Chris Rizos, Hermann Drewes and Harald Schuh). The valuable contributions of the reviewers are acknowledged in the 2016 document (Angermann et al. 2016).

It was proposed by the IAG Bureau (Zuheir Altamimi, Markku Poutanen and Richard Gross) that the review of this updated version should be conducted in the same way as for the first version. Thus, it has been suggested that each chapter/product of the inventory should be reviewed by experts in these fields. The list of rewiewers is provided in Table 2. The contributions by all reviewers and the suppport of the IAG Bureau are gratefully acknowledged by the authors.

Table 2: Reviewers designated by IAG to evaluate this document.

Chapter	Reviewers
Chapter 1.1	Markku Poutanen (Finland), Martin Sehnal (Austria)
Chapter 1.2	Michael Craymer (Canada), Markku Poutanen (Finland), Chris Rizos (Australia)
Chapter 2	Markku Poutanen (Finland), Martin Sehnal (Austria)
Chapter 3	Pavel Novák (Czech Republic), Nico Sneeuw (Germany)
Chapter 4.1	John Gipson (USA), Axel Nothnagel (Germany)
Chapter 4.2	Zuheir Altamimi (France), Thomas Herring (USA)
Chapter 4.3	Aleksander Brzezinski (Poland), Richard Gross (USA)
Chapter 4.4	Rolf Dach (Switzerland)
Chapter 4.5	Riccardo Barzaghi (Italy), Adrian Jäggi (Switzerland)
Chapter 4.6	Matt Amos (New Zealand), Dru Smith (USA)

1 Introduction

1.1 Global Geodetic Observing System (GGOS): Mission, goals and structure

The GGOS was initially created as an IAG Project during the International Union of Geodesy and Geophysics (IUGG) meeting in 2003 in Sapporo, Japan, in response to developments in geodesy, the increasing requirements of Earth observations, and growing societal needs. Since 2004, GGOS represents IAG in the Group on Earth Observation (GEO) and contributes to the Global Earth Observation System of Systems (GEOSS) (GEO 2005). After a preliminary development phase, the Executive Committee of the IAG decided to continue the Project at its meeting in August 2015 in Cairns, Australia. From 2005 to 2007, the GGOS Steering Committee, Executive Committee, Science Panel, Working Groups, and web pages were established. Finally, at the IUGG meeting in 2007 in Perugia, Italy, IAG evaluated GGOS to the status of a full component of IAG – as the permanent observing system of the IAG.

The IAG Services and Commissions provide the geodetic infrastructure and products, as well as the expertise and support for scientific developments, which are the basis for monitoring the Earth system and for global change research. GGOS relies on the observing systems and analysis capabilities already in place in the IAG Services and envisions the continued development of innovative technologies, methods and models to improve our understanding of global change processes. IAG and GGOS provide a framework that ranges from the acquisition, transfer and processing of a tremendous amount of observational data to its consistent integration. Consistency among the data sets from the different (geometric and gravimetric) observation techniques is of crucial importance for the generation of IAG products, such as geodetic reference frames which are the basis for the integration of geometry, Earth rotation and the gravity field (see Figure 1.1).

GGOS as an organisation is built upon the existing IAG Services as a unifying umbrella, and will continue to be developed for this purpose. Under this “unifying umbrella”, all the products provided by the different IAG Services are considered GGOS products – as ratified at the IAG General Assembly in 2009 in Buenos Aires, Argentina.

The mission and the overarching strategic focus areas of GGOS are specified in its Terms of Reference (see www.ggos.org). They were officially adopted by the IAG Executive Committee (EC) at the IUGG XXV General Assembly, Melbourne, Australia, 2011. Its first revision was approved by the IAG EC during the IUGG XXVI General Assembly, Prague, Czech Republic, 2015, and has been slightly revised in 2018.

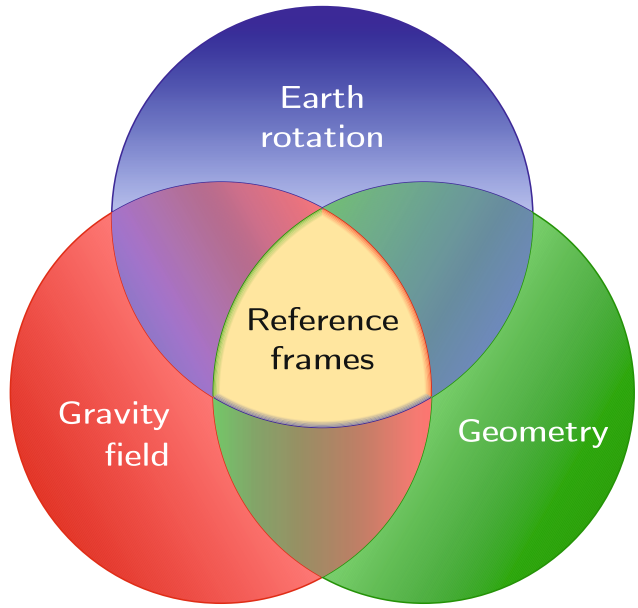


Fig. 1.1: Integration of the “three pillars” geometry, Earth rotation and gravity field (Rummel 2000), modified by (Plag and Pearlman 2009).

The mission of GGOS is:

1. To provide the observations needed to monitor, map and understand changes in the Earth’s shape, rotation, and mass distribution.
2. To provide the global geodetic frame of reference that is the fundamental backbone for measuring and consistently interpreting key global change processes and for many other scientific and societal applications.
3. To benefit science and society by providing the foundation upon which advances in Earth and planetary system science and applications are built.

The overarching strategic focus areas of GGOS goals and objectives are:

1. **Geodetic Information and Expertise**: GGOS outcomes will support the development and maintenance of organisational intangible assests, including geodetic information and expertise. The development of this strategic focus area will benefit all other goals and objectives.
2. **Global Geodetic Infrastructure**: Development of, advocacy for, and maintenance of existing global geodetic infrastructure is a direct support of each GGOS goal.
3. **Services, Standardisation, and Support**: Optimal coordination, support, and utilisation of IAG Services, as well as leveraging existing IAG resources, are critical to the progress of all GGOS goals and objectives.

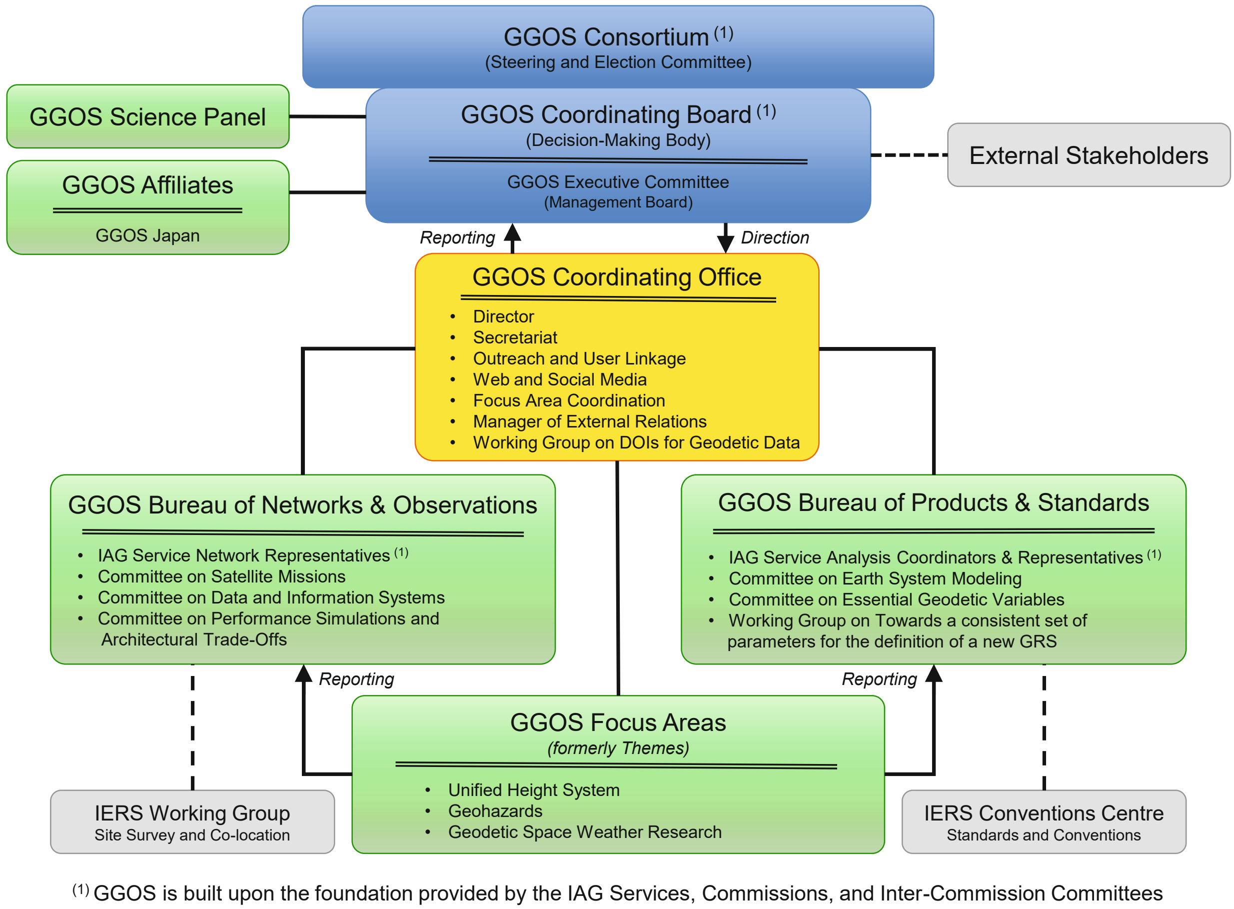


Fig. 1.2: Organisation structure of GGOS as adopted in December 2019.

4. **Communication, Education, Outreach**: Marketing, outreach, and engagement are critical elements for sustaining the organisational fabric of GGOS.

The organisational structure of GGOS is comprised of the following key components (see Figure 1.2):
GGOS Consortium – is the collective voice for all GGOS matters.
GGOS Coordinating Board – is the central oversight and decision-making body of GGOS, and represents the IAG Services, Commissions, Inter-Commission Committees, and other entities.
GGOS Executive Committee – serves at the direction of the Coordinating Board to accomplish day-to-day activities of GGOS tasks.
GGOS Science Panel – advises and provides recommendations relating to the scientific content of the GGOS 2020 to the Coordinating Board; and represents the geoscientific community at GGOS meetings.
GGOS Coordinating Office – coordinates the work within GGOS and supports the Chairs, the Executive Committee and the Coordinating Board; and coordinates GGOS external relations. Newly established components within the Coordinating Office are the position of the Manager of External Relations and the GGOS Working Group on “DOIs for Geodetic Data Sets”.

Bureau of Products and Standards (former Bureau for Standards and Conventions) – tracks, reviews, examines, evaluates the standards, constants, resolutions and conventions adopted by IAG or its components and recommends their continued use or proposes necessary updates; works towards the developement of new products derived from a combination of geometric and gravimetric observations.

Bureau of Networks and Observations (former Bureau for Networks and Communications) – develops strategies and plans to design, integrate and maintain the fundamental geodetic infrastructure, including communications and data flows; monitors the networks and advovates for implementation of core and co-located network sites and improved network performance.

GGOS Affiliates – are national or regional organisations that coordinate geodetic activities in that country or region. GGOS Affiliates allow increased participation in GGOS, especially by organisations in under-represented areas of Africa, Asia-Pacific, and South and Central America.

GGOS Committees, Working Groups and Focus Areas (formerly known as Themes) – address overarching issues common to several or all IAG components, and are a mechanism to bring the various activities of the Services, Commissions and Inter-Commission Committees together, or to link GGOS to external organisations. Focus areas are cross-disciplinary and address specific areas where GGOS contributors work together to address broader and critical issues.

IAG – promotes scientific cooperation and research in geodesy on a global scale and contributes to it through its various research bodies.

IAG Services, Commissions and relevant Inter-Commission Committees – are the fundamental supporting elements of GGOS.

GGOS Inter Agency Committee (GIAC) – was a forum that sought to generate a unified voice to communicate with Governments and Intergovernmental organisations (GEO, CEOS, UN bodies) in all matters of global and regional spatial reference frames and geodetic research and applications. GIAC was dissolved when the United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM) Working Group on the Global Geodetic Reference Frame (GGRF) was elevated to the permanent Subcommittee on Geodesy of the UN-GGIM.

UN Committee of Experts on Global Geospatial Information Management (UN-GGIM) – led by United Nations Member States, UN- GGIM aims to address global challenges regarding the use of geospatial information and to serve as a body for global policymaking in the field of geospatial information management.

Subcommittee on Geodesy (UN-GGIM) (SCoG) – provides an intergovernmental forum for cooperation and exchange of dialogue on issues relating to the maintenance, sustainability and enhancement of the Global Geodetic Reference Frame (GGRF).

1.2 Standards and conventions

Standards and conventions are used in a broad sense and a variety of international organisations and entities are involved. This section gives an overview of the standards and conventions that are currently in use within the geodetic community. According to Drewes (2008) and Angermann (2012) one can distinguish between standards, standardised units, fundamental physical standards, resolutions and conventions. In addition, the background models used for the data analysis are introduced in this section.

1.2.1 Standards

Standards are generally accepted specifications and measures for quantitative or qualitative values that define or represent under specific conditions the magnitude of a unit. A technical standard is an established norm or requirement, which is usually a formal document that provides uniform engineering or technical criteria, methods and processes or procedures.
Various international, regional and national organisations are involved in the development, coordination, revision, maintenance, etc. of standards that address the interests of a wide area of users. Important for geodesy is the International Organization for Standardization (ISO), an international standard-setting body composed of representatives from a network of national standards institutes of more than 150 countries. Many standards related to geographic information, including geodetic reference systems, have been or are being developed by ISO Technical Committee 211. ISO/TC211 (committee.iso.org/home/tc211) was established to cover the areas of digital geographic information and geomatics. It aims to establish a set of standards information concerning objects or phenomena that are directly or indirectly associated with a location relative to the Earth. These standards are linked to other appropriate ISO standards for information technology and data where possible, to provide a framework for the development of specific applications using geographic data. Some of the ISO standards related to geodetic reference systems include:

ISO 6709: Standard representation of geographic point location by coordinates (www.iso.org/standard/75147.html).

ISO 19111: Geographic information – Referencing by coordinates (www.iso.org/standard/74039.html).

ISO 19115-1: Geographic information – Metadata – Part 1 Fundamentals (www.iso.org/standard/53798.html).

ISO 19127: Geodetic Register (www.iso.org/standard/41784.html).

ISO 19135-1: Geographic information – Procedures for item registration (www.iso.org/standard/54721.html).

ISO 19161-1: Geographic information – The International Terrestrial Reference System (ITRS): definition, realisations and dissemination.

Also relevant for geodesy is the Open Geospatial Consortium (OGC), an international voluntary standards organisation, established in 1994. In the OGC, more than 400 governmental, commercial, nonprofit and research organisations worldwide collaborate in a consensus process encouraging the development and implementation of open standards for geospatial content and location-based services, Geographic Information System (GIS) data processing and data sharing.
The ISO and OGC standards are applied in geo-referencing, spatial analysis, and communication (service specification). There is a close cooperation between OGC, ISO/TC211 and IAG components. The chair and vice-chair of the Control Body for the ISO Geodetic Registry (geodetic.isotc211.org) are nominated by the IAG and the director of the BPS acts as the IAG liaison to ISO/TC211.

In February 2015, the UN General Assembly adopted its first geospatial resolution *"A Global Geodetic Reference Frame for Sustainable Development"*. The UN Committee of Experts on Global Geospatial Information Management (UN-GGIM) endorsed the GGRF Road Map and established a GGRF Working Group which became the UN-GGIM Subcommittee on Geodesy (SCoG) in 2017 (see www.un.org/en/ga/search/view_doc.asp?symbol=A/RES/69/266 and www.unggrf.org/). Within this SCoG five Working Groups (former Focus Groups) have been established, addressing the areas of Geodetic Infrastructure; Policies, Standards, and Conventions; Education, Training and Capacity Building; Outreach and Communications; and Governance. Implementation Plans have been developed by these Working Groups that were detailed in the GGRF Road Map. Recommendations of the Working Group on Policies, Standards and Conventions are:

- Member States support the efforts already undertaken by IAG and standards organisations, including ISO, towards geodetic standards and to make these standards openly available.
- Member States more openly share their data, standard operating procedures and conventions, expertise, and technology.
- Member States resolve their concerns that currently limit data sharing, as a valuable contribution to the enhancement of the GGRF.

The standards and conventions that are relevant for geodesy are based primarily on decisions made by international organisations or bodies involved in this topic, such as

- the Bureau International de Poids et Mesures (BIPM),
- the Committee on Data for Science and Technology (CODATA),

and by resolutions related to standards and conventions adopted by the Councils of

- the International Union of Geodesy and Geophysics (IUGG),
- the International Astronomical Union (IAU), and
- the International Association of Geodesy (IAG).

Within the IAU, Commission A3 "Fundamental Standards" (www.iau.org/science/scientific_bodies/commissions/A3) and the IAU's Standards of Fundamental Astronomy (SOFA) service (www.iausofa.org) are directly involved in standards.

1.2.2 Standardised units

In the International Vocabulary of Basic and General Terms in Metrology (BIPM 2006; ISO/IEC 2007) the terms *quantities* and *units* are defined. The value of a quantity is expressed as the combination of a number and a unit. In order to set up a system of units, it is necessary first to establish a system of quantities, including a set of equations relating those quantities. Binding for geodesy is the International System of Units (SI), which was adopted by the 11th General Conference on Weights and Measures (CGPM, 1960), and revised at its 26th meeting in 2018 (effective from 20 May 2019), see www.bipm.org/utils/common/pdf/CGPM-2018/26th-CGPM-Resolutions.pdf.

According to these CGPM Resolutions the SI is maintained by the BIPM. The units are divided into two classes – base units and derived units. In a similar way the corresponding quantities are described as base quantities and derived quantities. In the SI there are seven base units representing different kinds of physical quantities. Three of them are applied in geodesy:

- The *second*, symbol [s], is the SI unit of time. It is defined by taking the fixed numerical value of the caesium frequency $\Delta\nu_{\mathrm{CS}}$, the unperturbed ground-state hyperfine transition frequency of the caesium 133 atom, to be 9 192 631 770 when expressed in the unit Hz, which is equal to s^{-1}.
- The *metre*, symbol [m], is the SI unit of length. It is defined by taking the fixed numerical value of the speed of light in vacuum c to be 1/299 792 458 when expressed in the unit m/s, where the second is defined in terms of $\Delta\nu_{\mathrm{CS}}$.
- The *kilogram*, symbol [kg], is the SI unit of mass. It is defined by taking the fixed numerical value of the Planck constant h to be $6.626\,070\,15 \cdot 10^{-34}$ when expressed in the unit J s, which is equal to kg $\mathrm{m}^{-2}\,\mathrm{s}^{-1}$, where the metre and the second are defined in terms of c and $\Delta\nu_{\mathrm{CS}}$.

The number of derived units and derived quantities of interest in geosciences can be extended without limit. For example, the derived unit of speed is metre per second [m/s], or centimetre per second [cm/s] in the SI. Whereas the kilometre per hour [km/h] is a unit outside the SI but accepted for use with the SI. The same holds for the gal [$\mathrm{cm/s^2}$] which is a special non-SI unit of acceleration due to gravity.

The realisation of the SI at the BIPM constitutes a fundamental contribution to the tasks of the IAG. One of the five scientific departments of the BIPM, the "Time Department" has been a service of the IAG until the end of 2019. The activities of this department are focused on the maintenance of the SI second and the formation of the international reference time scales.

1.2.3 Fundamental physical constants

The formulations of the basic theories of physics and their applications are based on fundamental physical constants. These quantities, which have specific and universally used symbols, are of such importance that they must be known as accurately as possible. A physical constant is generally believed to be both universal in nature and constant in time. In contrast, a mathematical constant is a fixed numerical value, which does not directly involve any physical measurement. A complete list of all fundamental physical constants is given by the National Institute of Standards and Technology (NIST). NIST publishes regularly a list of the constants.

The CODATA is an interdisciplinary Scientific Committee of the International Science Council (ISC). IUGG and IAU are member unions of CODATA. The Committee works to improve the quality, reliability, management and accessibility of data. CODATA is concerned with all types of data resulting from measurements and calculations in all fields of science and technology, including physical sciences, biology, geology, astronomy, engineering, environmental science, ecology and others.

The CODATA Committee (former Task Group) on Fundamental Physical Constants was established in 1969. Its purpose is to periodically provide the international scientific and technological communities with an internationally accepted set of values for the fundamental physical constants. The first such CODATA set was published in 1973, and later in 1986, 1998, 2002, 2006, 2010 and 2014 (see, Mohr et al. 2016). The latest version, the 2018 least-squares adjustment of the values of the set of fundamental physical constants was released in 2019. The 2018 set replaces the previously recommended 2014 CODATA set and may also be found at www.physics.nist.gov/Constants. The fundamental physical constants are classified as universal, electromagnetic, atomic and nuclear, or physico-chemical constants as well as adopted values. The set of values provided by CODATA do not aim to cover all scientific fields. Only a few of these fundamental constants are relevant for geodesy, primarily two universal constants and two adopted values:

a) Universal constants
   - Newtonian constant of gravitation (G): $(6.674\,30 \pm 0.000\,15) \cdot 10^{-11}\,\mathrm{m^3 kg^{-1} s^{-2}}$
   - Speed of light in vacuum (c, c_0): $299\,792\,458$ m/s (exact)

b) Adopted values (as mean values at sea level)
   - Standard acceleration of gravity (g_n): $9.806\,65\ \mathrm{m/s^2}$ (exact)
   - Standard atmosphere (atm): 101 325 Pa (exact).

The astrogeodetic community needs, in addition to these fundamental physical constants, a set of suitable fundamental parameters as a basis for the definition and realisation of reference systems as well as for the generation of geodetic products. The geodetic activities in this field are addressed by the IERS Conventions Center (see Section 1.2.5) in cooperation with international organisations such as CODATA, IUGG and IAU. The present status of numerical standards used within IAG is discussed in Section 3.1.

1.2.4 Resolutions

A resolution is a written motion adopted by a deliberating body. The substance of the resolution can be anything that can normally be composed as a motion. In this context we refer to the motion for adopting standards, constants or any parameters to be used by institutions and persons affiliated with the adopting body. Most important resolutions for geodesy are those adopted by IUGG, IAG, and IAU. The IUGG and IAG resolutions are adopted at the IUGG General Assemblies and published every four years in the IAG Geodesist's Handbook (www.iag-aig.org/geodesists-handbook). They are also available at office.iag-aig.org/iag-and-iugg-resolutions.

The IAU resolutions are adopted by General Assemblies held every 3 years. They are published regularly in the IERS Conventions along with detailed information for their implementation (e.g., Petit and Luzum 2010). An electronic version can be obtained from www.iau.org/administration/resolutions.

Resolutions are non-binding laws of a legislature, but more binding than recommendations. In non-legal bodies, such as IUGG, IAG and IAU, which cannot pass laws, they represent the highest level of commitment. Resolutions shall be respected by all institutions and persons affiliated with the adopting body.

The resolutions, which are relevant with respect to standards and conventions for geodesy, are summarised below in chronological order. Please note that only some major information is extracted from the original resolutions. For the full version follow the links above.

IUGG Resolution No. 7 (1979) and **IAG Resolution No. 1 (1980)** on the Geodetic Reference System 1980 (GRS80) (Moritz 2000). It is recommended that the Geodetic Reference System 1967 shall be replaced by a new Geodetic Reference System 1980, also based on the theory of the geocentric equipotential ellipsoid.

IAG Resolution No. 16 (1983) on Tide Systems, recognising the need for the uniform treatment of tidal corrections to various geodetic quantities such as gravity and station positions. It is recommended that the indirect effect due to the permanent yielding of the Earth shall not be removed (IAG 1984).

IUGG Resolution No. 2 (1991) on the Conventional Terrestrial Reference System (CTRS) recommends that (1) CTRS to be defined from a geocentric non-rotating system by a spatial rotation leading to a quasi-Cartesian system; (2) the geocentric non-rotating system to be identical to the Geodetic Reference System (GRS) as defined in the IAU resolutions; (3) the coordinate-time of the CTRS as well as the GRS to be the Geocentric Coordinate Time (TCG); (4) the origin of the system to be the geocentre of the Earth's masses including oceans and atmosphere; and (5) the system to have no global residual rotation with respect to horizontal motions at the Earth's surface.

IAU Resolution A4 (1991) has set up a General Relativistic Framework to define reference systems centred at the barycentre of the solar system and at the geocentre.

IAU Resolution B2 (1997) on the International Celestial Reference System (ICRS). From January 1, 1998, the IAU celestial reference system shall be the ICRS. The corresponding fundamental reference frame shall be the International Celestial Reference Frame (ICRF) constructed by the IAU Working Group on Reference Frames. The IERS should take appropriate measures, in conjunction with the IAU Working Group on Reference Frames, to maintain the ICRF and its ties to the reference frames at other wavelengths.

IAU Resolution (2000) contains several specific resolutions (RES):

- **RES B1.1** Maintenance and Establishment of Reference Frames and Systems
- **RES B1.2** Hipparcos Celestial Reference Frame
- **RES B1.3** Definition of the Barycentric Celestial Reference System (BCRS) and Geocentric Celestial Reference System (GCRS)
- **RES B1.4** Post-Newtonian Potential Coefficients
- **RES B1.5** Extended Relativistic Framework for Time Transformations and Realisation of Coordinate Times in the Solar System
- **RES B1.6** IAU Precession-Nutation Model
- **RES B1.7** Definition of the Celestial Intermediate Pole
- **RES B1.8** Definition and Use of Celestial and Terrestrial Ephemeris Origins
- **RES B1.9** Re-definition of the Terrestrial Time (TT)
- **RES B2** Coordinated Universal Time (UTC).

The Resolutions B1.1 through B1.8 of the IAU General Assembly 2000 have been adopted by IUGG at its General Assembly in 2003 (see Resolution No. 4). More information on these resolutions may be found in the "Proceedings of the IERS Workshop on the Implementation of the New IAU Resolutions" published in the IERS Technical Note No. 29 (Capitaine et al. 2002).

IUGG Resolution 3 (2003) strongly supports the establishment of the GGOS (former IGGOS) Project within the new IAG structure as geodesy's contribution to the wider field of geosciences and as the metrological basis for the Earth observation programs within IUGG.

IAU Resolution B1 (2006) on adopting the P03 Precession Theory and Definition of the Ecliptic. It accepts the conclusions of the IAU Division I Working Group on Precession and Ecliptic (Hilton et al. 2006), and recommends that the terms lunisolar precession and planetary precession be replaced by precession of the equator and precession of the ecliptic, respectively, and that, beginning on 1 January 2009, the precession component of the IAU 2000A precession-nutation model be replaced by the P03 precession theory (Capitaine et al. 2003) in order to be consistent with both dynamical theories and the IAU 2000 nutation.

IAU Resolution B2 (2006) is a supplement to the IAU 2000 resolutions on reference systems, containing primarily two recommendations, the first to harmonise the name of the pole and origin to "*intermediate*" and a second recommendation fixing the default orientation of the BCRS and GCRS, which are assumed to be oriented according to the ICRS axes (for more information see the IERS Conventions 2010, Petit and Luzum 2010).

IAU Resolution B3 (2006) is on the re-definition of Barycentric Dynamical Time (TDB) (for more information see the IERS Conventions 2010, Petit and Luzum 2010). This resolution has also been adopted by the IUGG in 2007 as written in Resolution 1.

IUGG Resolution No. 2 (2007) on the Geocentric and International Terrestrial Reference System (GTRS and ITRS) endorses the ITRS as the specific GTRS for which the orientation is operationally maintained in continuity with past international agreements (BIH orientation), and adopts the ITRS as the preferred GTRS for scientific and technical applications, and urges other communities, such as the geo-spatial information and navigation communities, to do the same.

IUGG Resolution No. 3 (2007) on the Global Geodetic Observing System (GGOS) of the IAG. The new structure of IAG reflected by the designation of GGOS as a permanent component, urges sponsoring organisations and institutions to continue their support of the elements of GGOS, which is crucial for sustaining long-term monitoring and understanding of the Earth system.

IAU Resolution B2 (2009) on IAU 2009 Astronomical Standards. It recommends that the list of previously published constants compiled in the report of the IAU Division A Working Group Numerical Standards for Fundamental Astronomy (NSFA) (Luzum et al. 2011) be adopted as the IAU (2009) System of Astronomical Constants, that Current Best Estimates (CBE) of astronomical constants be permanently maintained as an electronic document, and that the IAU establish a permanent body to maintain the CBEs for fundamental astronomy.

IAU Resolution B3 (2009) resolves that from 01 January 2010 the fundamental astronomic realisation of the International Celestial Reference System (ICRS) shall be the Second Realization of the International Celestial Reference Frame (ICRF2) as constructed by the IERS/International VLBI Service for Geodesy and Astrometry (IVS) Working Group on the ICRF in conjunction with the IAU Division I Working Group on the International Celestial Reference Frame (Fey et al. 2009).

IUGG Resolution No. 3 (2011) on the ICRF2. This resolution urges that the ICRF2 shall be used as the standard for all future applications in geodesy and astrometry, and that the highest consistency between the ICRF, the ITRF, and the Earth Orientation Parameters (EOP) as observed and realised by the IAG and its components such as the IERS should be a primary goal in all future realisations of the ICRS.

IAU Resolution B2 (2012) on the re-definition of the Astronomical Unit of Length. It is recommended that the astronomical unit be re-defined to be a conventional unit of length equal to 149 597 870 700 m exactly, in agreement with the value adopted in IAU 2009 Resolution B2.

IAG Resolution No. 1 (2015) for the Definition and Realisation of an International Height Reference System (IHRS). It outlines five fundamental conventions for the definition of the IHRS, including a conventional value for the reference potential $W_0 = 62\,636\,853.4\ \mathrm{m^2 s^{-2}}$, and stating the mean tidal system/mean crust as the standard for the generation of IHRS-related products.

IAG Resolution No. 2 (2015) for the Establishment of a Global Absolute Gravity Reference System. It resolves, among other issues, to initiate the replacement of the International Gravity Standardization Net 1971 (IGSN71) by the new Global Absolute Gravity Reference System.

IUGG Resolution No. 3 (2015) on the Global Geodetic Reference Frame (GGRF) recognising the adoption in February 2015 by the General Assembly of the United Nations (UN) of a resolution entitled "A Global Geodetic Reference Frame for Sustainable Development". It urges the UN Global Geospatial Information Management (GGIM) GGRF Working Group to engage with IUGG and other concerned organisations such as the Committee of Earth Observation Satellites (CEOS) and the Group on Earth Observation (GEO), in order to promote the implementation of the UN GGIM GGRG RoadMap.

UN Resolution (2015) on a Global Geodetic Reference Frame (GGRF). The United Nations General Assembly adopted the resolution on a Global Geodetic Reference Frame for Sustainable Development (A/RES/69/266) on February 26, 2015.

IAU Resolution A1 (2018) on the IAU Strategic Plan 2020–2030.

IAU Resolution B1 (2018) on Geocentric and International Terrestrial Reference Systems and Frames. It recommends that the ITRS be adopted as the preferred GTRS for scientific and technical applications; and that the IAU engage, together with other concerned organisations such as the IUGG and IAG, with the United Nations (UN) Global Geospatial Information Management (GGIM) Subcommittee on Geodesy in order to promote the implementation of the UN-GGIM Road Map for the Global Geodetic Reference Frame.

IAU Resolution B2 (2018) on the Third Realisation of the International Celestial Reference Frame. It resolves that, as from 1 January 2019, the fundamental realisation of the International Celestial Reference System (ICRS) shall be the Third Realisation of the International Celestial Reference Frame (ICRF3), as constructed by the IAU Working Group on the Third Realisation of the International Celestial Reference Frame.

IAG Resolution No. 1 (2019) on the International Terrestrial Reference Frame (ITRF). It recommends to the user community that the ITRF be the standard terrestrial reference frame for positioning, satellite navigation and Earth science applications, as well as for the definition and alignment of national and regional reference frames.

IAG Resolution No. 2 (2019) on the Third Realisation of the International Celestial Reference Frame. It recommends (1) that the ICRF3 should be used as a standard for all future applications in geodesy and astrometry; (2) that the organisations responsible for geodetic VLBI observing programs take appropriate measures to continue existing and develop improved observing and analysis programs to both maintain and improve ICRF3, and (3) that highest consistency between the ICRF, the ITRF, and the EOP should be a primary goal in all future realisations.

IAG Resolution No. 3 (2019) on the Establishment of the International Height Reference Frame (IHRF). It urges all countries to engage with the IAG and concerned components, in particular the International Gravity Field Service (IGFS), in order to promote and support the implementation of the IHRF by (1) installing IHRF reference stations at national level; (2) conducting the necessary gravimetric surveys to guarantee the precise determination of potential values; (3) making data available open access; (4) contributing to the development of analysis strategies to improve the estimation of reference coordinates and modelling of the Earth's gravity field; and (5) describing, archiving and providing geodetic products associated to the IHRF.

IAG Resolution No. 4 (2019) on the Establishment of the Infrastructure for the International Gravity Reference Frame. It urges international and national institutions, agencies and governmental bodies in charge of geodetic infrastructure to (1) establish a set of absolute gravity reference stations on the national level; (2) perform regular absolute gravity observations at these stations; (3) participate in comparisons of absolute gravimeters to ensure their compatibility; and (4) make the results available open access.

IAG Resolution No. 5 (2019) on the Improvement of the Earth's Rotation Theories and Models. It resolves (1) to encourage a prompt improvement of the Earth rotation theory regarding its accuracy, consistency, and ability to model and predict the essential EOP; (2) that the definition of all the EOP, and related theories, equations, and ancillary models governing their time evolution, must be consistent with the reference frames and the resolutions, conventional models, products, and standards adopted by the IAG and its components; and (3) that the new models should be closer to the dynamically time-varying, actual Earth, and adaptable as much as possible to future updating of the reference frames and standards.

IUUG Resolution No. 2 (2019) on the International Terrestrial Reference Frame (ITRF). It resolves to recommend to the user community that the ITRF be the standard terrestrial reference frame for positioning, satellite navigation and Earth Science applications, as well as for the definition and alignment of national and regional reference frames.

1.2.5 Conventions

A convention is a set of agreed, stipulated or generally accepted norms, standards or criteria. In the Physical Sciences, numerical values such as constants or quantities are called conventional if they do not represent a measured property of nature, but originate from a convention. A conventional value for a constant or a specific quantity (e.g., the potential of the geoid W_0) can be, for example, an average of measurements agreed between the scientists working with these values.

In geodesy, conventions may be adopted by the IAG and its components (Services, Commissions, Inter-Commission Committees, and GGOS). Most established and common are the conventions of the IERS, which are provided by the IERS Conventions Center. These IERS Conventions are regularly updated and they serve as the basis for the analysis of the geometric observations and for the generation of IERS products. The IERS Conventions are based on the resolutions of the international scientific unions, namely the IUGG, IAU and IAG and they provide those constants, models, procedures, and software that have the most significance to IERS products (e.g., celestial and terrestrial reference frames, Earth orientation parameters, etc). Since these reference frames are based on the geometric measurement techniques GNSS, SLR/LLR, VLBI and DORIS, the IERS Conventions provide the basis for the work of the geometric services of the IAG: the International GNSS Service (IGS) (Dow et al. 2009), the International Laser Ranging Service (ILRS) (Pearlman et al. 2002), the International VLBI Service for Geodesy and Astrometry (IVS) (Schuh and Behrend 2012), and the International DORIS Service (IDS) (Willis et al. 2010).

The latest printed version are the IERS Conventions 2010 (Petit and Luzum 2010). They consist of eleven chapters that focus on topics, such as general definitions and numerical standards, the definition and realisation of the celestial and terrestrial reference systems, transformations between both systems, the geopotential, displacement of reference points, tidal variations in the Earth's rotation, models for atmospheric propagation delays, general relativistic models for space-time coordinates and equations of motion and general relativistic models for propagation. The official release of the IERS Conventions 2010 was on December 15, 2010. Updates are available at iers-conventions.obspm.fr/conventions_versions.php.

In 2018, the IERS Conventions Center released a Call to Participate in the IERS Conventions seeking volunteer participants as Chapter Editor-in-Chief, Chapter/Assistant Experts, and Software Editor to contribute to the revision of these conventions. The IERS Conventions Center intends to publish a new edition by 2022. Meanwhile, a team of experts for the revision of the IERS Conventions has been established and a work plan (including time schedule) has been defined by the IERS Conventions Center. The director of the BPS has been nominated as Chapter Expert for Chapter 1 "General definitions and numerical standards" and two representatives of the International Gravity Field Service (IGFS) accepted the invitation of the IERS Conventions Center to contribute to the rewriting of this chapter. Hence, for the first time, the gravity field community is directly involved in the development of definitions and numerical standards.

Although the IERS Conventions primarily serve as reference for the geometric observation techniques and products of the IERS, several parts of them also provide the basis for gravity-related data and products. However, for satellite gravity field missions (e.g., CHAMP, GRACE, GOCE), specific standards and conventions have to be used for the data analysis and product generation such as, e.g., EIGEN (Förste et al. 2012), GOCE (European GOCE Gravity Consortium 2014), EGM2008 (Pavlis et al. 2012). These gravity-related standards are not always fully consistent with the IERS Conventions, since also mission constraints (e.g., consistency with respect to former missions) have to be adhered to. Other satellite missions (e.g., altimetry, SAR, remote sensing, ...) are also often based on standards and conventions issued by the operating agencies such as ESA, CNES or NASA, which may also be different to the IERS Conventions.

In summary, there are currently different conventions in use for the analysis of geometric and gravimetric observations, which need to be carefully considered when different observation types are combined. This situation is not ideal for ensuring a consistent integration of the geometry, rotation and gravity field of the Earth, which is a key goal of GGOS. Thus, the development of a consistent set of conventions is an important requirement that the BPS will address.

1.2.6 Physical and empirical background models

The background models play an important role for the processing of the different space geodetic measurements and for the generation of geodetic products. This is a very broad topic since a large number of background models need to be applied to account for various geophysical phenomena and technique-specific effects. In this section we will address this topic only very shortly to give a brief overview and we refer to the IERS Conventions, which serve as the primary reference for the background models to be used for the analysis of the space geodetic measurements and the product generation. In addition to the IERS Conventions, the technique-specific IAG Services provide specific information for the corresponding space techniques.

Two types of correction models can be distinguished:

- Models to correct for the effect of geophysical phenomena that affect the station positions, quasar positions and/or satellite orbits (e.g., solid Earth tides, ocean tides, pole tides, etc).

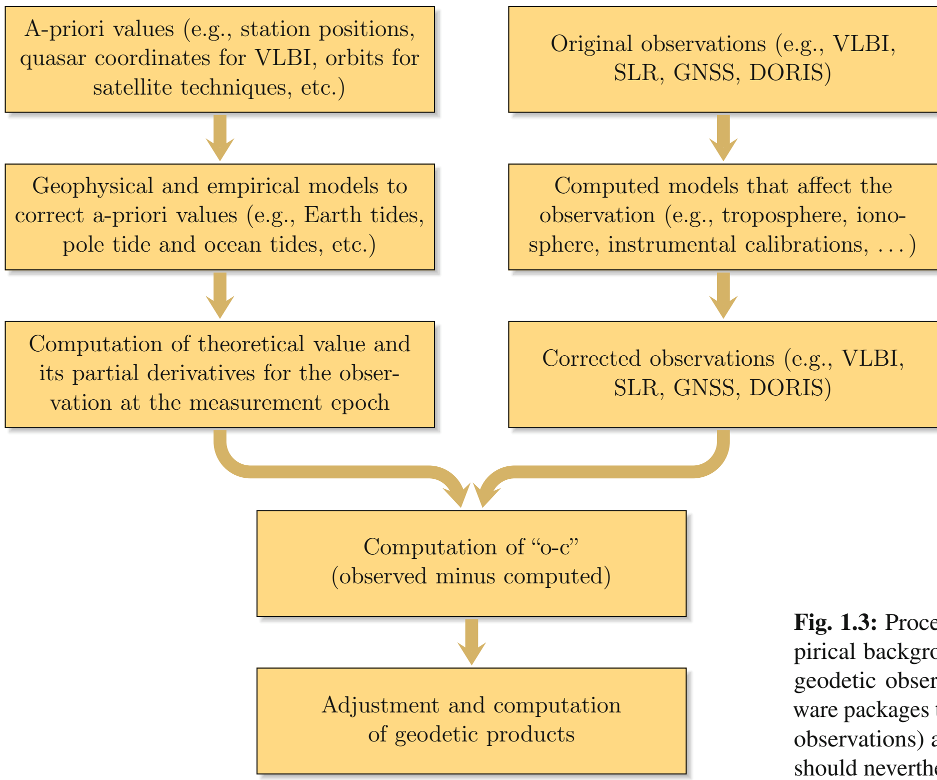


Fig. 1.3: Procedure for applying geophysical and empirical background models in the processing of space geodetic observations. Please note that in some software packages the second type of models (that affect the observations) are applied to the a-priori values, which should nevertheless lead to identical results.

- Models to account for effects that directly influence the space geodetic observations such as signal propagation (atmosphere) and technique-specific effects (e.g. GNSS antenna phase centre variations, thermal deformation of VLBI telescopes, SLR range biases, etc).

The first type of models are applied to the a-priori values for station coordinates, satellite orbits and quasar positions (in the case of VLBI), whereas the second type are generally computed in the observation space, but could also be applied to the a-priori values. The corrected a-priori values are then used to compute the theoretical geometry at the observation epoch. Finally, the values "o-c" (observed minus computed) are derived, and used as input for the adjustment procedure and the computation of geodetic products (see Figure 1.3). Concerning the background models, a further type of discrimination may be mentioned. While some models refer to a-priori fixed, fully determined values, some others use parameterised expressions; the parameter values are estimated within the least squares adjustment process related to the adjustment of the observations. Examples of the second type are, for example, parameters in the solar radiation pressure model or harmonic coefficients in the description of the Earth's gravitational potential.

Clearly these background models need to be developed with a specific level of accuracy and that these models have to be consistently applied according to well-defined standards and conventions. This is essential for the processing of the different space geodetic observations and a strong requirement for the generation of consistent geodetic products. The IAG Services are responsible for the definiton of the processing standards for their particular space gedetic technique, but this should be done in a coordinated way to ensure consistency of the derived products. Hence it is necessary to address this topic and a perfect forum for this are the Unified Analysis Workshops which take place every two years.

The evolution of the scope and accuracy of the space geodetic observations also requires a continuous improvement of the background models which should be used for the data analysis and which must be implemented in the various software packages. This is a continuous process involving many groups and institutions. A challenge is to ensure that the generation of the geodetic products is based on homogeneously processed observations. This holds in particular for the ITRF generation (see section 4.2), since it requires a unification of the models and processing standards among all the contributing analysis and combination centres of the geometric services as basis for a consistent reprocessing of the VLBI, SLR, GNSS, and DORIS data over the entire observation time spans for these space geodetic techniques. The Unified Analysis Workshops, the workshops of the geometric services and the IERS Directing Board meetings provide forums to discuss the relevant issues in detail.

2 GGOS Bureau of Products and Standards

The GGOS Bureau of Products and Standards (BPS) is a redefinition of the former GGOS Bureau for Standards and Conventions (BSC), which was established as a GGOS component in 2009. The BPS is operated by the Deutsches Geodätisches Forschungsinstitut, Technische Universität München (DGFI-TUM) and the Ingenieurinstitut für Astronomische und Physikalische Geodäsie of the Technische Universität München (IAPG) within the Forschungsgruppe Satellitengeodäsie (FGS) (Angermann et al. 2016, 2018; Hugentobler et al. 2012).

2.1 Mission and objectives

The Bureau of Products and Standards (BPS) supports GGOS in its goal to obtain consistent products describing the geometry, rotation and gravity field of the Earth. This is an important requirement for reliably monitoring global change phenomena (e.g., global sea level rise) and for providing the metrological basis for Earth system sciences. Figure 2.1 illustrates the integration of the "three pillars" geometry, Earth rotation and gravity field to obtain consistent geodetic products as the basis for studying the Earth system and the interactions between its sub-components and the outer space (e.g., Rummel, 2000; Drewes, 2007; Plag and Pearlman, 2009).

A key objective of the BPS is to keep track of adopted geodetic standards and conventions across all IAG components as a fundamental basis for the generation of consistent geometric and gravimetric products. The work is primarily build on the IAG Service activities in the field of data analysis and combinations. The BPS shall act as contact and coordinating point regarding homogenisation of standards and IAG products. Moreover, the BPS interacts with external stakeholders that are involved in standards and conventions, such as the International Organisation for Standardisation (ISO), the Committee on Data for Science and Technology (CODATA), the International Astronomical Union (IAU) and the UN GGIM Subcommittee on Geodesy (SCoG).

The objectives of the BPS may be divided into two major topics/activities:

- **Standards**: A key objective is the compilation of an inventory regarding standards, constants, resolutions and conventions adopted by IAG and its components. This includes an assessment of the present status, the identification of gaps and shortcomings concerning geodetic standards and the generation of the IAG products, as well as the provision of recommendations. It is obvious that such an inventory needs to be regularly updated since the IAG standards and products are continuously evolving. The BPS shall propagate standards and conventions to the wider scientific community and promote their use. Where necessary, the BPS should propose new standards. In this context, the BPS recommends the development of a new geodetic reference system, GRS20XX, based on the best estimates of the major parameters related to a geocentric level ellipsoid.
- **Products**: The BPS shall take over a coordinating role regarding the homogenisation of standards and geodetic products. The present status regarding IAG Service products shall be evaluated, including analysis and combination procedures, accuracy assessment with respect to

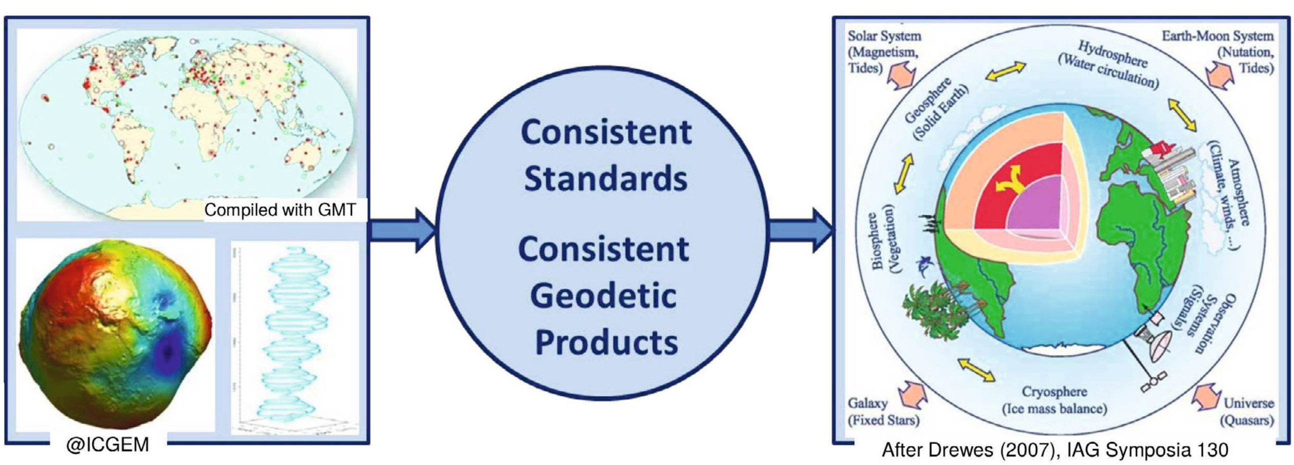


Fig. 2.1: The key role of standards and conventions for consistent geodetic products as the basis for Earth system research, for studying interactions between its sub-components and for precisely quantifying global change phenomena.

GGOS requirements, documentation and metadata information for IAG products. The Bureau shall initiate steps to identify user needs and requirements for geodetic products and shall contribute to develop new and integrated products. The BPS shall also contribute to the development of the GGOS Portal (as central access point for geodetic products), to ensure interoperability with IAG Service data products and external portals (e.g., GEO, EOSDIS, EPOS, GFZ Data Services).

2.2 Tasks

The tasks of the Bureau of Products and Standards are to:

- act as contact and coordinating point for homogenisation of IAG standards and products;
- keep track of adopted geodetic standards and conventions across all IAG components, and initiate steps to close gaps and deficiencies;
- interact with external stakeholders in the field of standards and conventions (e.g., IAU, ISO, BIPM, CODATA, UN-GGIM, ...);
- act as IAG representative to ISO/TC 211 and to the UN-GGIM GGRF Working Group “Data Sharing and Development of Geodetic Standards”;
- contribute to the UN GGIM Subcommittee on Geodesy (SCoG), mainly to the Working Group “Data Sharing and Development of Geodetic Standards”;
- regularly update the inventory on standards and conventions used for the generation of IAG products to incorporate the latest developments in these fields;
- contribute to the re-writing/revising of the IERS Conventions, mainly in the function as Chapter Expert for Chapter 1 “General definitions and numerical standards“;
- focus on the integration of geometric and gravimetric observations, and to support the development of integrated products (e.g., GGRF, IHRF, atmosphere products);
- contribute to the Committee on Essential Geodetic Variables (EGV), such EGVs could then serve as a basis for a gap analysis to identify requirements concerning observational properties and networks, accuracy, spatial and temporal resolution and latency;
- contribute to the newly established Working Group "Towards a consistent set of parameters for the definition of a new GRS";
- contribute to the GGOS Working Group on “DOIs for Geodetic Data Sets”, focusing on Digital Object Identifier (DOI) for geodetic data and products to improve discoverability of data sets and to ensure that data providers receive proper credit for their published data;
- organisational and coordination issues as well as representation and outreach activities, including internal BPS meetings (every two months), external Bureau meetings (twice per year), representing the BPS within IAG and at conferences and workshops, presentation and publication of BPS activities.

2.3 Staff and representation of IAG components and other entities

The present BPS staff members are Detlef Angermann (director), Thomas Gruber (deputy director), Michael Gerstl, Urs Hugentobler and Laura Sánchez (all from Technical University Munich), as well as Robert Heinkelmann (GFZ German Research Centre for Geosciences Potsdam) and Peter Steigenberger (German Aerospace Centre (DLR), Oberpfaffenhofen).

In its current structure, the following GGOS entities are associated with the BPS:

- Committee “Contributions to Earth System Modelling”, Chair: M. Thomas (Germany);
- Committee “Definition of Essential Geodetic Variables (EGVs)”, Chair: R. Gross (USA);
- Working Group “Towards a consistent set of parameters for the definition of a new GRS”,
  Chair: U. Marti (Switzerland).

According to its charter, the work of the BPS requires a close interaction with the IAG Analysis and Combination Centers regarding the homogenisation of standards and products. The IAG Services and the other entities involved in standards and geodetic products have chosen their representatives as associated members of the BPS. The Bureau comprises the staff members, the chairs of the associated GGOS components, the two committees and the working group as listed above, as well as representatives of the IAG Services and other entities. The status of December 2019 is summarised in Table 2.1. Regarding the development of standards, there is a direct link with the IERS Conventions Center, the IAU, BIPM, CODATA, ISO, and the UN-GGIM Subcommittee on Geodesy.

This configuration of the BPS ensures a close interaction with the IAG Services and the other entities involved in standards. A communication plan has been setup for a regular exchange of information, in particular regarding the homogenisation of standards and IAG products. Regular meetings of the BPS staff members take place in Munich every two months to perform the operational business. In addition regular telecons and face-to-face meetings (e.g., twice per year) with the BPS staff and the representatives (and invitees) take place to coordinate and manage the BPS work, to monitor progress against schedule, and to redefine tasks and responsibilites in case of need.

Table 2.1: Associated members of the BPS, representing the IAG Services, IAU and other entities (status: December 2019).

T. Herring, N. Stamatakos, USA	International Earth Rotation and Reference Systems Service (IERS)
U. Hugentobler, Germany	International GNSS Service (IGS)
E. Pavlis, USA	International Laser Ranging Service (ILRS)
J. Gipson, USA	International VLBI Service for Geodesy and Astrometry (IVS)
F. Lemoine, J. Ries, USA	International DORIS Service (IDS)
J.-M. Lemoine, H. Capdeville, France	International DORIS Service (IDS)
R. Barzaghi, Italy	International Gravity Field Service (IGFS)
S. Bonvalot, France	Bureau Gravimétrique International (BGI)
M. Reguzzoni, Italy	International Service for the Geoid (ISG)
E. S. Ince, Germany	International Centre for Global Earth Models (ICGEM)
K. M. Kelly, USA	International Digital Elevation Model Service (IDEMS)
H. Wziontek, Germany	International Geodynamics and Earth Tide Service (IGETS)
J. L. Hilton, USA	IAU Commission A3 Representative
M. Craymer, Canada	Chair of Control Body for ISO Geodetic Registry Network
L. Hothem, USA	Vice-Chair of Control Body for ISO Geodetic Registry Network
J. Ádám, Hungary	IAG Communication and Outreach Branch
D. Angermann, Germany	IAG representative to ISO/TC211
J. Kusche, Germany	Representative of gravity community

3 Evaluation of numerical standards

3.1 Defining parameters of geodetic reference systems, time and tide systems

The IUGG resolution No. 7 (1979) and the IAG resolution No. 1 (1980) recommend that the Geodetic Reference System 1980 (GRS80) (Moritz 2000) shall be used as the conventional reference for geodetic work. The GRS80 is defined by four constants GM, a, J_2 and ω, see Table 3.1. The GRS80 is now about 40 years old and thus these conventional constants do not represent anymore good estimates of parameters defining geometric and gravity field models best fitting to the shape and gravity field of the current Earth. In the concept of GRS80, the tidal systems and relativistic theories are not considered (Ihde et al. 2017). However, the IAG recommends the GRS80 parameters as a conventional ellipsoid, i.e., to convert Cartesian coordinates into ellipsoidal coordinates. The GRS80 ellipsoid is used worldwide for many map projections and millions of coordinates are related to it.

The numerical standards and adopted constants may also change with time, and so we should better speak about *fundamental parameters* instead of *constants* (Groten 2004). Since a substantial progress has been achieved in the estimation of these fundamental parameters and their temporal changes, the introduction of a new geodetic reference system (i.e., GRS2000) was a key topic within the geodetic community, in particular in Special Commission 3 “Fundamental Constants” (Groten 2004) of the IAG (in its old structure). However, after lengthy discussion and consideration, it was decided not to propose a new GRS at that time. Nevertheless, some progress was made and a consistent set of fundamental parameters and their current (2004) best estimates have been compiled (Groten 2004). The paper lists several possible values for the parameters. The set of constants defined in Section III of that paper is included in the IERS Conventions 2010 (Petit and Luzum 2010). Table 3.1 summarises the numerical standards given in different sources, namely the conventional GRS80 constants (Moritz 2000), the Earth Gravitational Model 2008 (EGM 2008), (Pavlis et al. 2012), the fundamental parameters of (Groten 2004), the IERS Conventions 2010, and the updated version (2017) of the IERS Conventions 2010 which contains the new conventional geopotential value W_0 issued in the IAG (2015) Resolution No. 1 (Drewes et al. 2016).

Various factors have to be considered for a comparison and interpretation of the values displayed in Table 3.1. The values are obtained from different sources aiming at different purposes. The GRS80 is still used to define a reference level ellipsoid and its normal gravity field (e.g., the IERS Conventions 2010, Chapter 4, recommend to use the GRS80 ellipsoid to compute geographical coordinates). Except for the angular rotation velocity ω, all other GRS80 parameters differ from the consistent set of fundamental parameters published by Groten about 25 years later (Groten 2004). For example, the difference for the equatorial radius a is about 0.4 m. The adopted standards for EGM 2008 were defined in the same geodetic reference system as adopted for EGM 96 (Lemoine et al. 1998) to ensure consistency between both gravitational field models. For a comparison of the values displayed in Table 3.1 it has also to be considered, that they are partly expressed in different time and tide systems.

In 2017, in cooperation between the IERS Conventions Center and the BPS, the IAG 2015 conventional value $W_0 = 62\,636\,853.4\,\mathrm{m^2 s^{-2}}$ has been updated in Chapter 1 of the IERS Conventions (Stamatakos 2017, pers. communication). Thus, the former difference beween the IERS Conventions 2010 value and the new IAG 2015 value of about $-2.6\,\mathrm{m^2 s^{-2}}$ (equivalent to a level difference of about 27 cm) has been resolved.

Without going into detail on time systems, it should be mentioned that the IUGG Resolution No. 2 (1991) recommends that the Geocentric Coordinate Time (TCG) shall be used for the geodetic reference system. In practice, however, analysis centres of all IAG geometric services use a time standard consistent with the Terrestrial Time (TT). As described in the IERS Conventions the relation between both time standards is given by the equation

$$L_G = 1 - d(\mathrm{TT})/d(\mathrm{TCG}) = 6.969290134 \cdot 10^{-10} \qquad (3.1)$$

Thus, the difference between both time standards and the corresponding length scales is about 0.7 ppb (parts per billion). Hence the value for the gravitational constant GM depends on the metric (see Table 3.1),

$$GM_{\mathrm{TT}} = GM_{\mathrm{TCG}}\,(1 - L_G)\,. \qquad (3.2)$$

It follows that the TT-compatible value of GM given for the EGM2008 standards is consistent with the TCG-compatible value given for the IERS Conventions 2010, see Table 1.1 of the IERS Conventions (Petit and Luzum 2010).

3.2 Solid Earth tide systems

Concerning the tide system, the IAG resolution No. 16 (1983) states that for the uniform treatment of tidal corrections to various geodetic quantities such as gravity and station positions, the indirect effect due to the permanent yielding of

Table 3.1: Comparison of numerical standards used within IAG.

	semi-major axis a [m]	Geocentric Grav. Constant GM $[10^{12} \mathrm{m}^3\mathrm{s}^{-2}]$	Dyn. form factor J_2 $[10^{-6}]$	Earth's rotation ω $[\mathrm{rad\ s}^{-1}]$	Reference potential W_0 $[\mathrm{m}^2\mathrm{s}^{-2}]$
GRS80	6 378 137	398.600 5	1 082.63	7.292 115	(1)
EGM2008	6 378 136.3	398.600 4415(2)	1 082.635 9	7.292 115	62 636 856.0
IERS Conv. 2010	6 378 136.6(3)	398.600 4418(4)	1 082.635 9	7.292 115	62 636 856.0
...(update 2017)					62 636 853.4(5)

(1)The reference potential U_0 of the GRS80 is 62 636 860.850 $\mathrm{m}^2\mathrm{s}^{-2}$;
(2)TT-compatible value; (3)value given in zero-tide system; (4)TCG-compatible value;
(5)value updated in the IERS Conv. 2010 in agreement with the conventional W_0 adopted by the IAG Resolution No. 1, 2015.

the Earth shall not be removed (IAG 1984). In the geodetic community the following different tidal systems are in use and have to be distinguished (Denker 2013; Mäkinen and Ihde 2009; Petit and Luzum 2010):

- In the *mean-tide system* only the periodic tidal effects are removed from the positions, but the permanent parts (both direct and indirect) are retained.
- The *zero-tide system* is the one recommended by IAG. In this system, the periodic tidal effects and direct permanent effects are removed completely, but the indirect deformation effects associated with the permanent tide deformation are retained.
- In the *tide free system* (or *non-tidal system*), the total tidal effects (periodic and permanent, direct and indirect) are removed with a model. In this case, the required (unobservable) fluid Love numbers have to be adopted by conventional values.
- The conventional routine for the evaluation of solid Earth tides computes tidal displacements as a sum of a frequency-independent closed form and a series of frequency-dependent corrections. The closed form includes a permanent tide which is wrongly multiplied with the nominal elastic Love number. Since for a long time the reduction of the wrong permanent part was disregarded, a separate tidal system was created which is now called *conventional tide free system*.

For geodetic products different tidal systems are being used. While the gravimetric services of IAG provide their products mostly in the zero-tide system, in agreement with the IAG resolution No. 16 of the 18^{th} IUGG General Assembly 1983, the geometric services supply their products, e.g., ITRF, in the conventional tide-free system. However, the ITRF has adopted, by convention, the same tide system as the analysis centres of IAG services. If the users need another tide system representation, the IERS Conventions provide the necessary conversion formulas in Chapter 7. In applications involving satellite altimetry, the mean-tide system is commonly used.

3.3 Open problems and recommendations

There are currently different numerical standards in use within the geodetic community. The parameters of the GRS80 are still used to define a reference level ellipsoid and normal gravity field of the Earth, although it represents the state-of-the-art of the 1970s (methods and data) and it also does not consider tidal effects and relativistic theories. The IERS Conventions 2010 (and its updates) are widely used within geodesy and they form the basis for processing of geometric observations and for generation of the IERS products. In addition to the IERS Conventions, various mission-dependent standards and conventions are used for gravity-related products and in satellite altimetry, which are often not fully consistent with the IERS Conventions. Another shortcoming of the current situation is that the conventional parameters are partly given in different time and tide systems, being a potential source of errors when combining different products.

The foundations of the IAG Resolution No. 16 (1983) are still valid concerning the tide systems. The recommended zero-tide system is the most adequate tide system for the gravity acceleration and potential of the rotating and deforming Earth. However, for the terrestrial reference system parameters the conventional tide free concept is used for decades, although the tide-free crust is far away from the real Earth's shape and it is unobservable. In the past, there have been several discussions on the tide system for the terrestrial reference frame. Due to practical reasons it was decided that it should not be changed. The current practice is to use the "conventional" tide-free system for geometry (ITRF), zero-tide system for gravity, mixed (mostly mean-tide system) for physical heights (derived from levelling), and mostly mean-tide system for satellite altimetry. This situation makes the use of geodetic products rather complicated and the inconsistent treatment of the permanent tide should be resolved within IAG.

Another issue concerns the time-tagging: at present, different space techniques and sometimes also different groups working within the same technique use different time standards, for example GPS time vs. UTC. The offset between different time standards does not affect the comparison of most geodetic parameters. However, if a particular parameter varies rapidly, such as ΔUT1, then it is important that the comparisons are done at the same epoch. Thus, it is recommended at a minimum that all scientists are clear and explicit about what time tags they are using. In a perfect world the same time tags would be used by everyone.

The IAG resolution No. 1 (2015) provides the basic conventions for the definition of an International Height Reference System (IHRS), being the IAG conventional W_0 value its fundamental parameter. In 2017, this value has been updated in the IERS Conventions 2010, so that W_0 is now uniquely defined in the geodetic standards. However, the current set of fundamental parameters do not fulfil the Somigliana-Pizzetti theory of the level ellipsoid. Thus, the definition of a new GRS is also needed from this point (see at the end of this section).

Another issue is the impact of the new W_0 value on the definition of time standards. Since L_G was declared as a defining constant by IAU in 1999, the relationship between TCG and TT does not depend anymore on the geoid realisation. The main implication for the IAU timescales is related to the accuracy in the realisation of the International Atomic Time (TAI). It presently corresponds to a coordinate timescale defined in a geocentric reference frame with the SI second as realised on the rotating geoid as the scale unit. Therefore, TAI still has a reference to the geoid (W_0), while TT does not have it anymore. This is a potential source of inconsistency because it is usually considered that TAI is a realisation of TT. However, this issue should not be further discussed here, since the TAI definition is under the responsibility of the General Conference of Weights and Measures through the Consultative Committee on Time and Frequency.

The current situation concerning the definition of numerical standards and the use of different time and tide systems within geodesy is a potential source for inconsistencies and even errors of geodetic products. Thus, it is essential for a correct interpretation and use of geodetic products that the underlying numerical standards are clearly documented. Moreover, if geodetic results expressed in different time or tide systems are combined, respective transformations have to be performed to get consistent results. As an ultimate goal all existing inconsistencies should be removed and a consistent set of standards and conventions should be developed.

As outlined in Ihde et al. (2017), IAG is considering the necessity and usefulness for replacing GRS80 by a new geodetic reference system. Towards this aim a new GGOS Working Group "Towards a consistent set of parameters for the definition of a new GRS" has been established as a component of the BPS at the end of 2019. This WG works together with representatives of IAG Commissions 1 and 2, the Inter-Commission-Committee on Theory (ICCT), the International Gravity Field Service (IGFS) and the Committee on Essential Geodetic Variables (EGV). The activities will focus on estimation of a new set of defining parameters for a modern GRS based on current methods and data, and on calculating all derived parameters in a consistent way. First results of such a consistent set of geodetic fundamental parameters have been derived and presented by Oshchepkov (2019). This set of defining parameters for a new GRS was derived in the zero-tide system and TT standard based on the Somiliana-Pizzetti theory of the level ellipsoid, comprising GM, U_0, J_2, and ω. Hence, the semi-major axis a would become a derived parameter. The BPS strongly recommends to work towards a new GRS as the basis for a consistent set of numerical standards to be used within IAG.

Summary of recommendations on the numerical standards, which have also been endorsed as recommendations of the Unified Analysis Workshops 2019 (Gross et al. 2019):

Recommendation 0.1 : The used numerical standards including time and tide systems must be clearly documented for all geodetic products.

Recommendation 0.2 : The inconsistency concerning the treatment of the permanent tide must be resolved within IAG to support the GGRF requirements and user needs.

Recommendation 0.3 : Astronomical, geodetic or geophysical standards including or requiring a W_0 reference value should adopt the IAG conventional W_0 value issued by the IAG Resolution No. 1 (2015), i.e., $W_0 = 62\,636\,853.4\ \mathrm{m^2 s^{-2}}$.

Recommendation 0.4 : A new Geodetic Reference System GRS20XX based on a consistent estimation of best estimates of the major parameters related to a geocentric level ellipsoid should be developed.

4 Product-based review

This chapter focuses on the assessment of the standards and conventions currently adopted and used by IAG and its components for the generation of IAG products. With the compilation of such a product-based inventory, the BPS supports GGOS in its goal to obtain consistent geodetic products and it provides also a fundamental basis for the integration of geometric and gravimetric parameters, and for the development of new products.

GGOS as an organisation is built on the existing IAG Services, and under this "unifying umbrella", all the products provided by the different IAG Services are considered GGOS products. This declaration and also Section 7.5 "Products available through GGOS" from the GGOS publication (Plag and Pearlman 2009) serve as the basis to specify the major products of IAG and GGOS, addressing the following topics:

Section 4.1 Celestial reference systems and frames,
Section 4.2 Terrestrial reference systems and frames,
Section 4.3 Earth orientation parameters,
Section 4.4 GNSS satellite orbits,
Section 4.5 Gravity and geoid,
Section 4.6 Height systems and their realisations.

The sections for each of these products (or topics) were organised in a similar structure. The first part gives a brief overview, followed by a description and discussion of the present status, and finally open problems are identified and recommendations are provided. Despite of this similar structure, the character of these sections is partly different as a consequence of the current situation regarding the availability of IAG products in the different fields and due to organisational issues of the IAG Services. Although the celestial reference frame is a product of IAU, it is addressed in this inventory, since IAG is directly involved through the IVS and the consistency between the celestial and terrestrial reference frame is also an important reseach topic of IAG (Section 4.1). Pure IAG products exist for the terrestrial reference frame (Section 4.2) and for the EOP (Section 4.3) which are provided by the responsible Product Centers of the IERS. This updated version of the inventory includes the latest version of these products, the ICRF3, the ITRF2014 and the EOP 14CO4 series. The GNSS satellite orbits addressed in Section 4.4 are provided by the IGS. This technique-specific product was included in the inventory, since the GNSS orbits are used for a wide range of applications. Also for the gravity field and geoid (Section 4.5) as well as for the height systems and their realisations (Section 4.6) a lot of progess has been achieved during the last four years, but on the other hand official IAG products still need to be defined and implemented. Due to this fact the character of these two corresponding sections differs from the four others.

The BPS gives credit to the efforts and contributions of the IAG Services, their contributing Analysis and Combinations Centers, and the Product Centers of the IERS and IGFS, which provide the foundation for the generation of the IAG Products. Without their significant work and valuable support the progress achieved during the past years would not have been possible.

Finally, it should also be noted that the list of topics and IAG products is by far not complete and it should be extended by adding other products in an updated version of this document, to incorporate the ongoing GGOS activities towards the development of integrated geodetic products.

4.1 Celestial reference systems and frames

4.1.1 Overview

By the nature of this topic, the IAU has always been responsible for celestial reference systems and celestial reference frames. However, in the course of technological development many more organisations and working groups have been involved in the more recent past where observations in the radio frequency regime have superseded optical observations. Due to its dominating volume of observations, the International VLBI Service for Geodesy and Astrometry (IVS) (Nothnagel et al. 2017) was the key supplier of observations and analysis capability in the recent past. The IVS was established in 1999 as an international collaboration of organisations operating or supporting VLBI components to support geodetic and astrometric work on reference systems and Earth science research by operational activities. Due to the basics of its technique, the IVS is a joint service of IAG and IAU. On the IAG side, the IVS represents the VLBI technique in GGOS and interacts closely with the IERS, which is tasked by IAU and IUGG with maintaining the ICRF and ITRF, respectively.

As a result of this organisational structure and technical infrastructure, the IAG, through IVS, has an indirect responsibility for the provision of the celestial reference frame at radio frequencies. The VLBI technique provides the direct link between the celestial and the terrestrial reference frames, and, at the same time, determines the Earth orientation parameters. Since the consistency between both frames is an important issue that should be addressed by the scientific community (see IUGG Resolution No. 3, 2011 and IAG Resolution No. 2, 2019), the topic is subject of this inventory.

The IAU resolution No. B2 from the IAU General Assembly in 1997 resolved (a) that as from 1 January 1998, the IAU celestial reference system shall be the International Celestial Reference System (ICRS) as specified in the 1991 IAU

Resolution on reference frames and as defined by the IERS (Arias et al. 1995); (b) that the corresponding fundamental reference frame shall be the International Celestial Reference Frame (ICRF) constructed by the IAU Working Group on reference frames; (c) that the Hipparcos Catalogue shall be the primary realisation of the ICRS at optical wavelengths; and (d) that the IERS shall take appropriate measures, in conjunction with the IAU Working Group on reference frames, to maintain the ICRF and its ties to the reference frames at other wavelengths. According to this IAU resolution, the ICRS has been realised by the ICRF since January 1, 1998, which is based on the radio wavelength astrometric positions of compact extragalactic objects determined by VLBI.

The IERS is responsible for monitoring the ICRS, maintaining its realisation, the ICRF, and improving the links with other celestial reference frames. Since 2001, these activities have been run jointly by the ICRS Centre (at the Observatoire de Paris and the US Naval Observatory) of the IERS and the IVS, in conjunction with IAU.

4.1.2 International Celestial Reference System

Following the IAU Resolution B2 (1997), the ICRS replaced the Fifth Catalogue of Fundamental Stars (FK5) as the fundamental celestial reference system for astronomical applications. According to IAU Resolution A4 (1991), the ICRS is a specific Barycentric Celestial Reference System (BCRS), with its axes kinematically non-rotating with respect to the distant objects in the universe (Petit and Luzum 2010). These axes are defined implicitly through a set of coordinates of extragalactic objects, mostly quasars, BL Lac sources and radio galaxies, all of which are Active Galactic Nuclei (AGN), as determined in the most precise realisation of the ICRS, the ICRF (for more information see (Petit and Luzum 2010)). The celestial reference system has its principal plane as close as possible to the mean equator at J2000.0 and the origin of right ascension on this principal plane as close as possible to the dynamic equinox of J2000.0.

4.1.3 International Celestial Reference Frames

History of ICRS realisations

The initial test realisation of the IERS Celestial Reference System, RSC(IERS) 88 C01 (Arias et al. 1988) contained 228 extragalactic radio sources in total. This first catalogue was computed by combining the VLBI solutions of three US agencies (Goddard Space Flight Center (GSFC) and Jet Propulsion Laboratory (JPL), both belonging to the National Aeronautics and Space Administration (NASA), and National Geodetic Survey (NGS)). In the adjustment process the right ascension of the source 3C273B was fixed to its conventional FK5 value (Hazard et al. 1971). 23 out of the 228 radio sources were chosen to define the axis directions of this first frame. This initial realisation can be considered as the intangible basis of the radio celestial frame, since all subsequent realisations directly or indirectly refer to this initial set of coordinate axes. Between 1988 and 1994, several celestial reference frames were determined on a regular basis following the first one, all of which were referred to the respective previous realisation of ICRS by No-Net-Rotation (NNR) constraints.

As specified in the IAU Resolution No. 2 (1997), the ICRF, i.e. the first conventional realisation of the ICRS, is based on the positions of extragalactic objects provided by VLBI. Adopted by the IAU Working Group on Reference Frames (WGRF), it was determined by the VLBI solution of the GSFC (Ma et al. 1998; Ma and Feissel 1997). The catalogue provides the positions and uncertainties of 608 radio sources, including 212 defining sources used for the global NNR condition, to realise the axes of the ICRF (Arias and Feissel 1990) with respect to previous IERS celestial reference frames (Arias et al. 1991; Ma and Feissel 1997).

There were two extensions of ICRF: ICRF-Ext. 1 (Gambis 1999) and ICRF-Ext. 2 (Fey et al. 2004). For both extensions the original ICRF positions of the defining sources remained unchanged, thus preserving the initial ICRF orientation fixed.

Within the common IAU/IVS Working Group entitled "The Second Realisation of the International Celestial Reference Frame – ICRF2" a new version of ICRF was computed (Fey et al. 2009, 2015), which was accepted by the IAU at its General Assembly in Rio de Janeiro, Brazil, in August 2009 (see IAU Resolution No. B3, 2009) and by IUGG Resolution No. 3 (2011). It contains the positions of 3414 compact radio sources, including a selected set of 295 defining sources. The stability of the axes is specified to be 10 μas, making ICRF2 nearly twice as stable as its predecessor, also accompanied by an improved noise level of about 40 μas and a more uniform sky distribution including more defining sources on the southern hemisphere.

The overall characteristics of the ICRF2 solution are described in (Fey et al. 2009, 2015). The a-priori models for geophysical effects and precession/nutation used for the computations generally followed the IERS Conventions 2003 (McCarthy and Petit 2003). Specifically, corrections for solid Earth tides, the pole tide, ocean loading, and high frequency EOP variations were made using the IERS Conventions 2003. Other important effects were modelled using

- atmosphere pressure loading corrections according to Petrov and Boy (2004),
- troposphere delays based on the Vienna Mapping Functions 1 (VMF1) of Böhm et al. (2006),
- the antenna thermal deformation models of Nothnagel (2009), and

- the a-priori gradient model according to MacMillan and Ma (1997).

The current realisation, the ICRF3

Within the IAU Division A Working Group entitled "Third Realisation of the International Celestial Reference Frame (ICRF3)" a new version of ICRF was computed (Charlot et al. 2020), which was accepted by the IAU at its General Assembly in Vienna, Austria, in August 2018 (see IAU Resolution No. B2, 2018). The developments were supported by the IAG Sub-Commission 1.4 "Interaction of Celestial and Terrestrial Reference Frames". The reliability of the ICRF3 could be improved through comparisons with observations obtained at higher radio frequencies and at optical wavelength provided by European Space Agency (ESA)'s optical astrometry mission Gaia.

The ICRF3 contains the positions of 4536 compact radio sources, including a selected set of 303 defining sources. The stability of the axes betters the one of the previous reference frame, ICRF2. Individual coordinates show a noise floor of about 30 μas. For the first time, the effects of galactic rotation on celestial coordinates is considered in the ICRF3 in terms of a correction on the observation level. Therefore, the reported celestial coordinates refer to the epoch 2015.0. Besides the S-/X-band coordinates, ICRF3 contains several hundreds of objects in K- and/or X-/Ka-bands as well. A comparison of ICRF3 with data release 2 (DR2) of the ESA Gaia mission in optical wavelengths shows no deformations above about 30 μas. Mainly due to the revisiting of ICRF2 survey radio sources, the source coordinate errors have a more uniform sky distribution. Accordingly, the ICRF3 only contains the radio source categories "defining" and "candidates". A comparison with Gaia and ICRF2 revealed that the ICRF2 has small systematic deformations of up to 80 μas.

The a-priori models for geophysical effects and precession/nutation used for the ICRF3 computations generally followed the IERS Conventions 2010 (Petit and Luzum 2010). Specifically, corrections for solid Earth tides, the pole tide, ocean loading, and high frequency EOP variations comply with that conventions. Besides the conventional models mentioned above, other important effects were modelled using tidal and non-tidal atmosphere pressure loading corrections according to Petrov and Boy (2004) instead of the tidal-only atmosphere pressure loading model mentioned in the IERS Conventions 2010.

4.1.4 Discussion of the present status

General issues

The organisational structure regarding the definition and realisation of the celestial reference system is rather complex. Quite a large number of organisations, services and other entities are involved. Although the responsibilities for the definition of the ICRS and the maintenance of the ICRF are resolved in the IAU resolutions (see Sections 1.2.4 and 4.1.1), the complex structure in this field requires an efficient and regular exchange of information to ensure effectiveness of the work.

ICRS definition and its realisation

The definition and realisation of the ICRS are given in the IERS Conventions (Petit and Luzum 2010) on the basis of several IAU resolutions. The IAU Resolution A4 (recommendation VII, 1991) recommends under (1) "*that the prinicipal plane of the new conventional celestial reference frame be as near as possible to the mean equator at J2000.0 and that the origin of the principal plane be as near as possible to the dynamical equinox of J2000.0*". These rather imprecise definitions result from the fact that old realisations were usually not as precise as the subsequent conventional realisations. A series of ICRS realisations has been computed so far, and in each of those the datum has been defined with respect to the previous realisation by applying NNR conditions. But this is depending on the quality, number and distribution of the defining radio sources used in the NNR condition. When applying this procedure, inconsistencies of the predecessor can affect the reference frame definition (mainly the orientation) of new (more precise) frames.

ICRF computations

All ICRS realisations including the latest one, the ICRF3, have been computed by only one IVS Analysis Center using a single software package. Although the final product is controlled through a comparison with individual IVS solutions, the procedure differs from the generation of the ITRF and EOP products, which are generated from a combination of individual contributions (see Section 4.2 and 4.3). Currently, formal errors of the ICRF determined by VLBI are certainly too optimistic since they do not account for uncertainties of a number of technique-specific models and auxiliary observations such as atmospheric pressure and air temperature. Other examples of neglect are antenna axis offsets, thermal expansion modelling, uncertain technique-specific model components and source structure effects. Although, the imbalance of VLBI observatories on the northern and southern hemispheres has been improved for the ICRF3, the impact of such an effect has to be investigated in more detail.

Consistent estimation of the ICRF, ITRF and EOP

The IUGG Resolution No. 3 (2011) urges that the highest consistency between the ICRF, the ITRF and the EOP as observed and realised by IAG and its components such as the IERS should be a primary goal in all future realisations of the ICRS. The newly adopted IAG Resolution No. 2 (2019) recommends that highest consistency between the ICRF, the ITRF, and the EOP should be a primary goal in all future realisations. At present, both frames (the ICRF and ITRF) and the EOP solutions are not fully consistent with each other as they are computed independently by separate IERS Product Centers. Although the recommendations of the IUGG and IAG resolutions have not been fulfilled yet, related studies are being performed by several research groups (e.g., at JPL and Deutsches Geodätisches Forschungsinstitut, Technische Universität München (DGFI-TUM)), see for example, Seitz et al. (2014), Kwak et al. (2018), and Soja et al. (2019). On the international level, this topic has been addressed by the IAU Working Group “ICRF 3” and it is an ongoing research topic of the IAG Sub-Commission 1.4 “Interaction of celestial and terrestrial reference frames”. The topic of the consistency between the ICRF, ITRF, and EOP is addressed at Sections 4.2 and 4.3 as well.

4.1.5 Interaction with other products

Through the VLBI observations there is a direct link of the celestial reference frame with

- terrestrial reference frames and
- the Earth orientation parameters.

The interactions of the ICRF with the ITRF and EOP also provide indirect links to the dynamic reference frames of satellite orbits and to other parameters derived from the mentioned products.

4.1.6 Open problems and recommendations

General issue on ICRS/ICRF

As a consequence of the interactions between IAU and various IAG components, the celestial reference system and frame is part of this inventory, although the latest ICRF3 realisation is labeled as IAU product. It helps to address important scientific questions, like the consistency between the celestial and terrestrial frame. Moreover, the objectives of GGOS require not only an Earth-fixed frame, but also the link to an inertial frame and the interactions between both described by the EOP, which is also relevant for the implementation of the GGRF.

ICRF computations

It remains to be considered whether the next ICRS realisation shall be estimated from a combination of different analysis centre solutions computed with different software packages, as done by the other Product Centres of the IERS. The precision of the coordinates of radio sources forming the ICRF steadily gets better due to more accurate observations and improved analysis methods. Therefore, it shall be investigated if source position instabilities must be included. Recent studies on source structure effects were performed by Anderson et al. (2019).

Consistency of ICRF, ITRF and EOP

This topic was already addressed at the IERS Retreat in Paris 2013 (see www.iers.org/IERS/EN/Organization/Workshops/Retreat2003.html).
In the above mentioned IERS Retreat 2013, it was recommended that the following questions should be addressed: (1) How consistent is the ICRF with the ITRF and EOP ? (2) Is the ICRF decoupled enough from the ITRF so that radio sources do not need to be included in the ITRF computations and vice versa? (3) What is the gain if ICRF, ITRF and EOP are estimated in a common adjustment? Although the studies mentioned in Section 4.1.4 show already some quality improvements due to the combined adjustment of the celestial and terrestrial reference frame and the EOP, the questions above still need to be addressed in more detail. Thus, research groups that can do the required combinations are encouraged to perform such studies. On the international level the IAG Sub-Commission 1.4 “Interaction of celestial and terrestrial reference frames” and the proposed IAG/IERS/IAU JWG on the Consistency of CRF, TRF, and EOP should also focus on this important topic.

Summary of recommendations on ICRS/ICRF

Recommendation 1.1 : The organisations involved in the definition and realisation of the ICRS are asked to clarify the structure and responsibilities. This is also important in the framework of the implementation of the GGRF, which includes the ICRF.

Recommendation 1.2 : It should be considered by the organisations and their responsible working groups, whether the next ICRS realisation, should be estimated from a combination of different analysis centre solutions.

Recommendation 1.3 : Research groups are encouraged to perform further investigations on source structure effects and to evaluate the impact on the realisation of the celestial reference system.

Recommendation 1.4 : Following IUGG Resolution No. 3 (2011) and IAG Resolution No. 2 (2019), research groups are encouraged to perform the previously mentioned studies regarding the consistency of ICRF, ITRF and EOP. Please note that this recommendation also concerns the Sections 4.2 and 4.3.

4.2 Terrestrial reference systems and frames

4.2.1 Overview

A Terrestrial Reference System (TRS) is a spatial reference system co-rotating with the Earth. Its realisation is called a *reference frame*. The nomenclature and basic concepts of a terrestrial reference system and the frame are well described in Chapter 4 of the IERS Conventions 2010 (Petit and Luzum 2010). The most recent update of Chapter 4 (v1.3.0 of April 2019) is available at iers-conventions.obspm.fr/content/chapter4/icc4.pdf.

Terrestrial reference frames (TRF) are needed to refer the geodetic observations and estimated parameters to a unified global basis. High accuracy, consistency and long-term stability are required for precisely monitoring global change phenomena as well as for precise positioning applications on and near the Earth's surface. The importance of geodetic reference frames for many societal and economic benefit areas has been recognised by the United Nations too. In Feburary 2015, the UN General Assembly adopted its first geospatial resolution "A Global Geodetic Reference Frame for Sustainable Development" (see www.un.org/en/ga/search/view_doc.asp?symbol=A/RES/69/266 and www.unggrf.org/).

The International Terrestrial Reference System (ITRS) has been formally adopted and recommended for Earth science applications (IUGG 2007). The IAG Resolution No. 1 (2019) recommends to the user community that the ITRF should be the standard terrestrial reference frame for positioning, satellite navigation and Earth science applications, as well as for the definition and alignment of national and regional reference frames. The IERS is in charge of defining, realising and promoting the ITRS. The IERS Conventions provide the basis for the general definitions and numerical standards as well as for the mathematical representation of the relevant quantities and for the modelling of the contributing geometric space techniques.

The International Terrestrial Reference Frame (ITRF) is a realisation of the ITRS, consisting of 3-dimensional positions and time variations of IERS network stations observed by space geodetic techniques. Currently, the contributing space techniques are VLBI, SLR, GNSS, and DORIS. According to the Terms of Reference of the IERS, the ITRS Center hosted at the Institut National de l'Information Géographique et Forestiere, France (IGN), is responsible for the maintenance of the ITRS/ITRF, including network coordination, for providing the ITRS Combination Centers with specifications, and for evaluating their respective results. The ITRS Combination Centers are responsible to provide ITRF products by combining ITRF inputs from the Technique Centers and others. ITRS Combination Centres are currently maintained by IGN (Paris, France), DGFI-TUM (Munich, Germany) and JPL (Pasadena, USA).

4.2.2 History of ITRS realisations

Until now, thirteen releases of the ITRF were published by the IERS, starting with ITRF 88 and ending with ITRF 2014, each of which superseded its predecessor (see Chapter 4 of the IERS Conventions 2010, (Petit and Luzum 2010)). An updating of ITRS realisations is performed every few years, since the tracking networks of space techniques are evolving, the period of data extends, and also the modelling and data analysis strategies as well as the combination methods improve with time. Furthermore, several large earthquakes might have affected station positions and velocities over large regions. Up to ITRF 2000, long-term global solutions (comprising station positions and velocities) from the four techniques (VLBI, SLR, GNSS, and DORIS) were used as input for the ITRF generation, which have been used by the ITRS Centre at IGN in France to compute the ITRS realisations.

In 2001, when the IERS was restructured, the newly established ITRS Center (former ITRS Terrestrial Reference Frame Section) has been supplemented by ITRS Combination Centers, to enable intercomparisons of the ITRF results. Additionally, the combination strategy for the ITRF computations has been refined. Starting with ITRF 2005, the ITRF computations were based on time series of station positions and EOP, including variance-covariance information from each of the techniques' combination centres. The ITRF 2005 and 2008 solutions were computed at the ITRS Combination Centers operated by IGN and DGFI. A comparison and discussion of the ITRF2008 (Altamimi et al. 2011) and the DTRF2008 (Seitz et al. 2012) is provided in the 2016 version of this inventory (Angermann et al. 2016). The current ITRS realisation, the ITRF2014, is summarised in Section 4.2.3.

In January 2019, the IERS disseminated a call for participation for a new ITRF2020 solution to be released by the ITRS Center at the end of 2021. This new ITRS realisation will contain six years of additional observations until the end of 2020. New sites have been added to the ITRF network and new colocation sites as well as new local ties are now available. Moreover, the geometric IAG Services have further improved their processing strategies, new models have been implemented and the ITRS Combination Centers have refined their combination methodologies.

4.2.3 The current ITRS realisation, the ITRF 2014

The ITRF 2014 is the current realisation of the ITRS (Altamimi et al. 2016). It is based on reprocessed solutions or normal equations of the four space techniques VLBI, SLR, GNSS, and DORIS comprising time series of station positions and EOP. They are generated by individual analysis centres of the technique-specific IAG Services, namely the IGS, ILRS, IVS and IDS. In the ITRF 2014 call for participation it was specified that the input data shall conform to the IERS Conventions 2010 (Petit and Luzum 2010). Moreover, guidelines for the ITRS Combination Centers were provided in this call. The time series cover the entire observation history for each of the four techniques and the individual contributions were combined per-technique by the responsible technique-specific combination centres of the IGS, ILRS, IVS, and IDS. The major characteristics of the input data for the ITRF 2014 are given in Table 4.1.

The ITRF2014 is generated with an enhanced modelling of nonlinear station motions, including seasonal (annual and semi-annual) signals of station positions and post-seismic deformation (PSD) for sites that were subject to major earthquakes. In case of ITRF2014 and for stations subject to PSD, the user should add the sum of all PSD corrections to the linearly propagated position, using equation 4.16 of the most recent update of Chapter 4 of the IERS Conventions (iers-conventions.obspm.fr/content/chapter4/icc4.pdf):

$$\vec{X}(t) = \vec{X}(t_0) + (t - t_0)\dot{\vec{X}} + \delta\vec{X}_{\mathrm{PSD}}(t)$$

The ITRF2014 PSD parametric models, together with all equations allowing users to compute the PSD corrections and Fortran subroutines are available at the ITRF2014 website itrf.ign.fr/ITRF_solutions/ITRF2014.

Compared to the ITRF2008, the input data for the ITRF2014 were significantly improved. Besides six more years of observations, also technical upgrades of satellite and station equipment as well as a higher number of stations and satellites allows for a more robust realisation of the ITRS. Moreover, the entire observation time series for all techniques were reprocessed by using the latest technique-specific and geophysical background models (as specified in the IERS Conventions 2010 and its updates) and, if appropriate, by implementing new parameterisations. Table 4.2 summarises the most important changes in modelling and parameterisation from ITRF2008 to ITRF2014.Detailed information for each of the four techniques is provided in the references given in Table 4.2.

In addition to the local ties used in the ITRF2008 computation, a certain number of new local ties from new colocation sites and/or from new surveys were used for the ITRF2014 (Altamimi et al. 2016).

These input data were used by the three ITRS Combination Centers at IGN (France), DGFI-TUM (Germany) and JPL (USA) to compute the ITRS realisations, i.e., the ITRF 2014 (Altamimi et al. 2016), the DTRF 2014 (Seitz et al. 2020, 2016) and the JTRF 2014 (Abbondanza et al. 2017). While DTRF 2014 and ITRF 2014 are secular frames providing station positions at a reference epoch and constant velocities according to the conventional ITRS definition, the JTRF 2014 is based on a KALMAN filter approach delivering time series of station positions. Thus, the two conventional multi-year solutions computed at IGN and DGFI-TUM are not directly comparable with the JTRF 2014 time series of weekly station position and EOP solutions. The characteristics of these three solutions are summarised in Table 4.3.

The ITRS combination strategies have been substantially improved compared to the ITRF2008 computations. The ITRF2014 involves two main innovations dealing with the modelling of non-linear station motions, namely seasonal signals present in the time series and post-seismic deformation (PSD) for stations subject to major earthquakes. Also the DTRF2014 is characterised by two main innovations: For the first time, it considers non-tidal loading corrections derived from geophysical models. Secondly, it provides as additional DTRF2014 products the time series of the station position residuals, the weekly SLR translation parameters and the non-tidal loading (NT-L) corrections, which were provided by the GGFC (Tonie van Dam). The ITRS Combination Center at JPL provided its first ITRS realisation, the JTRF2014, in the form of time series of weekly solutions comprising station positions and EOP.

The IERS Technical Note on the ITRF2014 (Altamimi et al. 2017) is supplemented by an additional IERS Technical Note

Table 4.1: Input data sets for ITRF 2014 (TC: Techniques' Combination Center, AC: Analysis Center, NEQs: Normal Equations). In addition, also geodetic local tie information is used as input for the ITRF computations.

TC	# ACs per technique	Time period	Sampling	Data	Constraints
IGS	9	1994.0 – 2015.1	Daily	Solutions	Minimum
IVS	9	1980.0 – 2015.0	Daily	NEQs	None
ILRS	7	1983.0 – 1993.0	Fortnightly	Solutions	Loose
ILRS	8	1993.0 – 2015.0	Weekly	Solutions	Loose
IDS	6	1993.0 – 2015.0	Weekly	Solutions	Minimum

Table 4.2: New models and parameterisations applied by the geometric technique services for the generation of the ITRF2014 input data; the table has been taken from (Seitz et al. 2020) and has been slightly modified.

Technique	Service	Model changes and new parameterisation
DORIS	IDS	IDS input data for ITRF2014 (Moreaux et al. 2016) - models improvements of some satellites (Envisat, Cryosat-2, Jason-2) - parameterisation of antenna frequency offsets - most recent time-variable gravity field EIGEN-6S2 (Förste et al. 2012) - improved modelling of radiation pressure accelaration - refined modelling of atmospheric drag - satellite attitude laws in POD software has been re-verified by some ACs - timetagging for Envisat solved - SAA effects on SPOT-5 oscillator solved
GNSS	IGS	IGS input data for ITRF2014 (Rebischung et al. 2016) - switch from weekly to daily resolutions - implementation of IGb08/igs08.atx reference frame - implementation (partly) of new attitude models for ecclipsing satellites - modelling of Earth radiation pressure, and (mostly) of antenna thrust
SLR	ILRS	ILRS input data for ITRF2014 (Luceri and Pavlis 2016) - four satellites: Lageos 1/2 and Etalon 1/2 - daily mean pole values derived from IERS series - centre-of-mass correction for each satellite in specific tables - modelling or estimation of range corrections for a number of sites
VLBI	IVS	IVS input data for ITRF2014 (Bachmann et al. 2016) - provision of celestial pole offsets - fixing of source positions to ICRF2 (Fey et al. 2015) - new axis offsets and eccentricities
general models	IERS	General models according to IERS Conventions 2010 (Petit and Luzum 2010) - mean pole model (all, except ILRS as given above) - Earth's gravity field model - tidal station displacements - tidal variations in Earth rotation - Nutation model - relativistic effects - tropospheric and ionospheric propagation delays

(Altamimi and Dick 2020). It includes the two other ITRS solutions, the DTRF2014 and JTRF2014, a comparision of the three solutions performed at IGN and DGFI-TUM as well as evaluations of the three ITRS solutions done by the IERS Technique Centers, which provide the input data for the ITRF generation. Such Technique Center contributions have been provided by the IDS, ILRS and IVS. These evaluations confirm the high quality of the three ITRS solutions as well as the improvement compared to the ITRF2008.

This IERS Technical Note 40 (Altamimi and Dick 2020) gives credit to the various contributions to the ITRF2014, which yield an excellent basis for the ITRF2014 evaluation. However, concerning the ITRF accuracy, it should be noted that the cross-validations of the three ITRS solutions (which are based on the same input data) are mainly a measure for their consistency, and they do not fully reflect the various impact factors that need be considered to quantify the accuracy of the terrestrial reference frame (see Section 4.2.4).

4.2.4 Discussion of the present status

ITRS definition vs. its realisation

According to the IERS Conventions (Petit and Luzum 2010), the ITRS definition is based on the following principles:

- It is geocentric, the centre of mass being defined for the whole Earth, including oceans and atmosphere;
- The unit length is the meter (SI). This scale is consistent with the TCG time coordinate for a geocentric local frame, in agreement with IAU and IUGG (1991) resolutions;
- Its orientation was initially given by the Bureau International de l'Heure (BIH) orientation of the BIH Terrestrial System (BTS) at epoch 1984.0;

Table 4.3: Summary of combination strategies for the ITRF2014, DTRF2014 and JTRF2014 (PSD: Post-seismic deformation, NT-L: Non-tidal loading). More details on the combination strategies are found in the references for the ITRF2014 (Altamimi et al. 2016), the DTRF2014 (Seitz et al. 2020) and JTRF2014 (Abbondanza et al. 2017).

Solution	ITRF2014	DTRF2014	JTRF2014
Institute	IGN (Paris, France)	DGFI-TUM (Munich, Germany)	JPL (Pasadena, USA)
Software	CATREF	DOGS-CS	CATREF + KALMAN
Combination approach	Solution (parameter) level	Normal equation level	Solution (parameter) level
Station position	Position $\mathbf{X}_{\mathrm{ITRF}}(t_0)$ + velocity $\dot{\mathbf{X}}_{\mathrm{ITRF}}(t_0)$ + PSD models (selected stations) + periodic signals (on request)	Position $\mathbf{X}_{\mathrm{DTRF}}(t_0)$ + velocity $\dot{\mathbf{X}}_{\mathrm{DTRF}}(t_0)$ + NT-L models + SLR origin + residual station motions	Weekly positions $\tilde{\mathbf{X}}_{\mathrm{ITRF}}(t_i)$
Earth orientation parameters	*Combined:* – Terrestrial pole (PM), – PM rates from GNSS and VLBI *Separate VLBI-only:* – dUT1, – LOD, – Celestial pole	*Combined:* – Terrestrial pole (PM), – PM rates from GNSS and VLBI, – LOD from GNSS + SLR + VLBI *Separate VLBI-only:* – dUT1, – Celestial pole	*Combined:* – Terrestrial pole (PM), – PM rates from GNSS and VLBI *Separate VLBI-only:* – dUT1 – Celestial pole

- The time evolution of the orientation is realised by using a no-net-rotation (NNR) condition with regard to horizontal tectonic motions over the whole Earth.

In the following, we compare the ITRS definition with its realisation:

Origin: The ITRF origin is realised by SLR observations. Through the orbit dynamics, SLR determines the Centre of Mass (CM). According to the IERS Conventions 2010 (Petit and Luzum 2010), the ITRF2014 and DTRF2014 origin follows the mean Earth centre of mass, averaged over the time span of SLR observations used and modelled as a secular (linear) function in time. It can be regarded as a *crust-based* TRF with the origin realised as a mean CM (Blewitt 2003; Dong et al. 2003; Petit and Luzum 2010; X. Wu et al. 2015). However, various geophysical applications and precise orbit determination require station coordinates to be referred to the instanteneous CM. To obtain such an instantaneous geocentric position, it is recommended in the IERS Conventions (Petit and Luzum 2010) to substract the so-called geocentre motion (i.e. the vector from the crust-based ITRF origin to the instanteneous centre of mass) from the ITRF position. However, the expression "geocentre motion" is defined differently in the geodetic literature (e.g., Dong et al. 2003), and moreover, a commonly accepted model to account for this effect is not available yet. The ITRF2014 provides an annual geocentre motion model derived from the same SLR data that define the ITRF2014 long-term origin (Altamimi et al. 2016). The DTRF2014 delivers the time series of the SLR translation parameters as an additional product (Seitz et al. 2016), and the JTRF2014 realises the origin at the quasi-instanteneous CM as sensed by SLR (Abbondanza et al. 2017). Although SLR is the most precise observation technique to realise the ITRS origin, it has to be considered that the SLR results may be affected by the so-called *network effect* due to a relatively sparse network and due to the blue-sky effect if atmospheric loading is not considered (Collilieux et al. 2009).

Scale: The ITRS scale is specified to be consistent with the TCG coordinate time (IAU and IUGG resolutions, 1991), whereas its realisation is consistent with the terrestrial time (TT). The difference between both time scales dTT/dTCG is about 1 - 0.7 $\cdot$ 10^{-9} (see Section 3.1), equivalent to a height difference of 4.5 mm at the surface of the Earth. The ITRS scale is realised by SLR and VLBI observations and, similar as for the origin, the results are affected by relatively sparse networks. In the ITRF2014 computations, IGN estimated a scale difference between VLBI and SLR of 1.37 ppb at epoch 2010.0 (Altamimi et al. 2016), whereas the DTRF2014 did not exhibit such a scale discrepancy. Based on the scale tests performed at DGFI-TUM, which did not show a significant scale offset between VLBI and SLR, the DTRF2014 scale was realised as a weighted mean of the SLR and VLBI scale (Seitz et al. 2020). In contrast to DTRF and JTRF, the ITRF2014 includes a scale factor between SLR and VLBI as unknown parameter in the combination model. The scale issue is an ongoing topic mainly of the ILRS, the IVS and the ITRS Combination Centres.

Orientation and its time evolution: The orientation of the coordinate axes of the reference frame could, theoretically, also be defined by the Earth's gravity field, namely the second degree spherical harmonic coefficients which are related to the orientation of the principal axes of inertia. This definition of the orientation is not used in practice because its determination is not as precise as for the origin, and the satellite orbits are not so sensitive with respect to its variations. Instead, these reference frame parameters are realised by external NNR conditions. This is done by successive transformations with respect to the previous ITRF realisation. Thus, its realisation depends on the network geometries and the stations used for the definition, including the weighting. The orientation rate of the ITRF2000 was aligned to that of the geophysical model NNR-NUVEL-1A (Argus and Gordon 1991; DeMets et al. 1990, 1994). The succeeding realisations, i.e., the ITRF2005, ITRF2008 and ITRF2014, were conventionally realigned to its predecessor. As deformation zones are neglected in the geophysical model and plate motions are averaged over long time periods (up to 1 Myr), there are differences with respect to present-day motions (Altamimi et al. 2012; Argus et al. 2011; DeMets et al. 2010; Drewes 2009; Kreemer et al. 2006). According to Drewes (2012), the resulting station velocity differences are of 1.1 mm/yr around a rotation pole with a latitude of about $-60°$ and a longitude of about $120°$. The first version of this inventory also provides an alternative concept by defining "absolute" plate motions with respect to the Earth's mantle by moving hot spots. Such a "hot-spot" model might be useful for geophysical considerations, but it is not compliant with the ITRS definition.

Input data for ITRF computations

For a particular ITRS realisation, the specifications for the input data, i.e. solutions and/or normal equations in SINEX format, are given in the call for participation of the IERS, which is released by the ITRS Center. Such a call specifies which parts of the IERS conventions should be obeyed, including updates. It is also stated that, whenever deviations from the recommendations of the IERS Conventions are preferred, it is requested that the effects of those deviations are documented.

Each intra-technique solution is a combination of several Analysis Centre (AC) solutions as shown in Table 4.1 (these are 9 individual solutions for GNSS and VLBI, 8 for SLR, and 6 for DORIS). Moreover, different software packages are in use by the ACs for processing space geodetic observations. Although much care is taken by the ACs to provide data that are fully consistent with these definitions, the current status is that this information is not always clearly (or fully) documented and, in some cases, the corresponding AC log-files are not up to date. Thus, it is difficult to assess the impact of possible deviations, if some of the input data are not fully in accordance with the adopted standards and conventions.

Furthermore, different subsets of the available data are used by the services for generating the ITRF input data, e.g., in case of GNSS, different station networks are selected by the ACs. In addition, some ACs only use GPS and some use GPS and GLONASS, but other GNSS are not considered by the IGS up to ITRF2014. Thus, the IGS input data for the ITRF2014 are different in terms of network geometries and the included GNSS data. In case of SLR, low spherical satellites and tracking data to GNSS satellites are not used in ILRS computations. The ILRS is performing various tests on the inclusion of additional satellites in order to enhance future SLR contributions to the ITRF.

Modelling of station positions and displacements

The instantaneous position of a station $X(t)$, which is fixed to the Earth's crust, is defined in Chapter 4 of the IERS Conventions 2010 (Petit and Luzum 2010) as the sum of a regularised station position $X_R(t)$ and conventional corrections $\sum_n \Delta X_n(t)$,

$$X(t) = X_R(t) + \sum_n \Delta X_n(t). \tag{4.1}$$

In the conventional secular approach, the regularised station position itself is parameterised by a linear model describing the position at any epoch t_i by the position at the reference epoch t_0 plus a constant velocity multiplied by the time difference $(t_i - t_0)$

$$X_R(t_i) = X_R(t_0) + \dot{X}(t_0) \cdot (t_i - t_0). \tag{4.2}$$

According to the IERS Conventions 2010 (Petit and Luzum 2010), the displacements of reference markers on the crust are modelled by conventional correction models, considering the effects on stations due to solid Earth tides, ocean loading, rotational deformation caused by polar motion and ocean pole tide loading. Even if these various effects are conventionally modelled, one has to keep in mind that model uncertainties, and possible model errors could affect the corrections of the instantaneous station positions. Such errors and also other effects (that are not considered in the conventional corrections) will become visible as residuals in the position time series.

The updated version of Chapter 4 of the IERS Conventions (iers-conventions.obspm.fr/content/chapter4/icc4.pdf) specifies the regularised coordinates of ITRF stations as parametric functions of time. They are composed of:

- Station positions at a reference epoch and station velocities until ITRF2008. Note that station velocities were taken from geophysical models before ITRF91.

- Station positions at a reference epoch, station velocities and post-seismic deformation (PSD) functions for some stations in ITRF2014.

The time series analysis reveals non-linear motions of several millimeters or even more (up to a few centimeters) for some stations. These motions are caused by various effects that are not properly modelled or for which accurate models are not available (e.g., Bevis and Brown 2014; Blossfeld et al. 2014; X. Wu et al. 2015). Various investigations (e.g., van Dam et al. 2012; Davis et al. 2012) have shown that periodic variations in the time series of station positions with amplitudes up to a few centimeters are caused by neglected surface loading and other (unmodelled) effects. In the study of Ray et al. (2013), it was found that non-tidal loading deformation does not explain more than half of the vertical annual variations in GNSS station position time series and much less in the horizontal components. Roggenbuck et al. (2015) compared loading models for atmosphere, ocean and hydrology and studied the impact on global SLR, VLBI and GNSS solutions. Männel et al. (2019) studied the surface loading corrections for VLBI and GNSS networks at the observation level. The DTRF2014 applied non-tidal loading corrections for atmosphere and hydrosphere by using models provided by Tonie van Dam (personal communication). The results show that the seasonal variations in the residual time series for station positions and datum parameters (origin and scale) could be significantly reduced (compared to the standard DTRF2014 solution without applying loading corrections).

Furthermore, some stations are located in deformation zones and are affected by post-seismic behaviour after strong earthquakes (e.g., Freymueller 2010; Sánchez et al. 2013). These effects are modelled by exponential post-seismic correction models in ITRF2014 and by a piecewise linear function representation in DTRF2014, whereas the post-seismic behavior is directly captured by the time series-based JTRF2014. A few stations are also affected by anthropogenic effects like, e.g., yearly groundwater withdrawal (Bawden et al. 2001). A dominant source for producing non-linear station motions are systematic errors and technique-specific effects. Examples are modelling discrepancies of the technique-dependent internal reference points, such as GNSS phase centre offsets and variation models for satellites and stations (Schmid et al. 2016) and corrections for radio antenna thermal deformations (Nothnagel 2009) as well as draconitic variations in GNSS positions (Amiri-Simkooei 2013).

Integration of space techniques at colocation sites

A major limiting factor for the integration of the different space geodetic techniques, the inter-technique combination, is the rather inhomogeneous and relatively sparse distribution of colocation sites. In total, 139 local tie SINEX files available for 91 colocation sites (with two or more technique instruments which were or are currently operating) were used in the ITRF2014 (Altamimi et al. 2016). There are not so many colocations between VLBI, SLR and DORIS, and thus, GNSS plays a major role in linking together these three techniques. In total, there are 212 tie vectors between GNSS and the reference points of the three other techniques: 62 to VLBI, 50 to SLR, and 67 to DORIS (Altamimi et al. 2016). On the other hand, the large number of GNSS discontinuities is critical for the combination of GNSS with the other three techniques. The discrepancies between the terrestrial local tie vectors and the space geodetic solutions are a good quality measure for the accuracy of the terrestrial reference frame. According to Altamimi et al. (2016), more than half of the colocations show tie discrepancies larger than 5 mm. The full list of local tie discrepancies is available at the ITRF2014 website. The interpretation of these discrepancies is a challenge, since various impact factors have to be considered such as systematic errors of the space techniques, uncertainties for the definition of the reference points, local site instabilities, outdated local surveys, largely different observation epochs for "old" instruments as well as uncertainties of the terrestrial local tie measurements.

4.2.5 Interaction with other products

The ITRF is a key geodetic product, that provides the basis for precise positioning on the Earth's surface and for Earth orbiters as well as for many practical applications (e.g., navigation, surveying, mapping) and for Earth sciences. How well the reference frame can be realised has important implications for Earth system studies and for monitoring global change phenomena such as sea level rise. There is an interaction between the terrestrial reference frame and all other products addressed in this inventory, such as

- Celestial reference frames
- Earth orientation parameters
- Satellite orbits
- Gravity field models
- Heights

4.2.6 Open problems and recommendations

Reference frame definition

The ITRF origin follows the average CM, realised (linearly with time) by SLR data (Altamimi et al. 2016). However, satellite precise orbit determination and various demanding applications require station coordinates refering to the instantaneous CM. Although the ITRF2014 provides an annual geocentre motion, which allows the computation of such an instantenous CM, the sparseness of the ILRS network along with its temporal variations hinders the highly precise determination of the SLR-derived geocentre motion (X. Wu et al. 2012). Thus, this topic needs to be further studied and it is recommended to include other methods and data for the estimation of the geocentre motion.

The scale of the ITRS is defined in TCG time scale (consistent with IAU and IUGG (1991) resolutions), whereas its realisation refers to TT. To avoid inconsistencies, the relation between both time scales (see equation 3.1) must always be considered correctly if observations and/or products refer to different time systems. Concerning the realisation of the scale, in the ITRF2014 a significant scale offset between VLBI and SLR was estimated (Altamimi et al. 2016). Although the recent estimation of range biases by the ILRS seems to largely explain the scale offset, this issue needs to be further investigated by the ILRS and IVS together with the ITRS Combination Centres and it should be studied in the framework of the upcoming ITRF2020 computations.

The orientation of the ITRS is realised by external NNR conditions, whereas for each particular realisation successive transformations with respect to the previous ITRF realisation have been performed. Consequently, this procedure depends on the network geometries and the stations used for the transformations. The orientation rate of ITRF2014 as well was successively transformed to that of ITRF2000, which was aligned to that of the geological model NNR-NUVEL-1A, as outlined in Section 4.2.4.

Input data for ITRF computations

In practice, it is questionable, whether all partial solutions for the ITRF are based on exactly the same standards and conventions. To get an overview about the present situation it is recommended that the Services (IGS, ILRS, IVS, IDS) together with all contributing ACs compile documentation of the standards and conventions currently applied in the software packages used for the data processing. Such a compilation of the processing standards has been performed already by the IDS, which is given as an example. A table summarizing the standards that are used by the IDS Analysis Centers with respect to their ITRF2014 submissions is available at ids-doris.org/combination/contribution-itrf2014.html. The efforts of the IGS to tabulate models used by its Analysis Centers should also be mentioned. For this purpose, the corresponding information is summarised on a Google docs spreadsheat and can be updated by the IGS Analysis Centers to reflect model updates. These efforts should be continued (and strengthened) by the IAG Services to ensure that the processing standards are consistently applied by all Analysis Centers as a prerequisite for consistent products.

Handling of non-linear station motions

Although a significant progress concerning the handling of non-linear station motions has been achieved in the framework of the ITRF2014, this topic is subject of further research. The fact that the three ITRS Combination Centres applied different approaches to account for non-linear station motions is beneficial to do comparisons between them and to perform detailed studies on this issue. Moreover, a comparison of the different observation time series at colocation sites provides valuable information to separate geophysical effects from technique-specific effects. Following the recommendations of the ITRF2020 call for participation and the Unified Analysis Workshop 2019 (Gross et al. 2019), the GGFC should be invited to provide a unified loading model including all contributions (atmosphere, hydrology, and ocean) for all ITRF2020 sites.

Integration of space techniques

The observed discrepancies at colocation sites (which exceed 5 mm for more than half of the colocations) are a major limiting factor for the integration of the different geodetic space techniques. A challenge is the separation of the different impact factors that need to be considered (see Section 4.2.4). A problem in this context is the sparse distribution of high-quality colocation sites. Colocation with GNSS plays a dominant role for the integration of the different techniques, but the large number of GNSS discontinuities is critical. Thus, it is an overall goal to improve the spatial distribution of colocation sites and the availability of precisely measured local ties. However, the required maintenance, sustainability and enhancement of the geodetic infrastructure goes beyond the responsibilities of IAG, and it involves activities on the political level, such as those of the UN-GGIM Subcommittee on Geodesy, which provides an intergovernmental forum for cooperation and exchange of dialogue on these issues. In addition to the *classical* colocation on Earth, a challenge for the future would be the colocation of sensors in space.

Taking into account the current deficiencies and open problems mentioned above, it is obvious that the ITRF accuracy requirements (formulated by IAG/GGOS) at a level of 1 mm and the stability of 0.1 mm/yr are not achieved yet, and probably exceeded by a factor of about 5 to 10.

The following recommendations on the ITRS/ITRF are provided:

Recommendation 2.1 : ITRF defining parameters: The realisation of the ITRF origin, scale, orientation and their time evolution should be consistent with the ITRS definition. Concerning geocentre models, it is recommended to supplement the ITRF2014 geocentre model by other methods and data and to compare the results between different geocentre models. The SLR and VLBI scale issue should be further studied.

Recommendation 2.2 : ITRF input data: In order to get consistent ITRF results, the input data should be based on unified standards and conventions, such as the latest version of the IERS Conventions. The Services (IGS, ILRS, IVS and IDS) and their contributing ACs should provide the relevant information on the status of the standards and conventions currently applied in the data processing.

Recommendation 2.3 : Non-linear station motions: The handling of non-linear station motions should be further studied. The GGFC should be invited to provide a unified loading model including all contributions (atmosphere, hydrogolgy, and ocean) for all ITRF2020 sites (see recommendations of the ITRF2020 CfP and the Unified Analysis Workshop 2019).

Recommendation 2.4 : Integration of space techniques: The station networks and the spatial distribution of high quality colocation sites should be further improved to achieve a more stable integration of the different space techniques. This overall recommendation goes beyond IAG responsibilities, as an improvement of the geodetic infrastructure involves the political level and funding issues. In addition to the colocation on Earth, the benefits of the colocation in space should be studied. This recommendation is fundamental to achieve the IAG/GGOS accuracy requirements for the terrestrial reference frame and to ensure its long-term stability.

Recommendation 2.5 : ITRF evaluation: The availability of three ITRF solutions ensures an evaluation of the quality of the final product. The IERS Technical Note 40, comprising the individual contributions and the product evaluation is gratefully acknowledged and it is recommended that also for upcoming ITRS realisations such a Technical Note is compiled.

4.3 Earth Orientation Parameters (EOP)

4.3.1 Overview

Earth orientation and Earth rotation are two aspects of the same physical effect. Earth rotation describes the change of the orientation of the Earth's body with respect to a space fixed reference frame. Astronomy, satellite geodesy, or precise navigation require an accurate knowledge of the orientation of the Earth in a quasi inertial reference frame. Various disciplines of geosciences depend on the gravitational and geodynamic impact of rotation. Earth rotation is one of the impulses of the dynamics of the Earth system and the interactions between individual components, such as the exchange of angular momentum between atmosphere, ocean and solid Earth, or the coupling mechanism between the Earth's core and mantle (Plag and Pearlman 2009; Seitz and Schuh 2010). Both requirements, orientation and rotation, will be fulfilled if the Earth Orientation Parameters (EOP) are given as functions of time, usually as a combination of diurnal time series with analytic models.

Practically, the EOP are the parameters representing the rotational part of the transformation between two reference frames, a terrestrial and a celestial frame. According to the definition by the IERS, these two frames are actual realisations of the geocentric International Terrestrial Reference System (ITRS) and the Geocentric Celestial Reference System (GCRS) or the Barycentric Celestial Reference System (BCRS):

$$\text{ITRS} \xrightarrow{\text{rotation}} \text{GCRS} \xrightarrow{\text{translation}} \text{BCRS}.$$

The ITRS orientation is given by the IUGG Resolution 2 (2007). It is operationally maintained in continuity with past international agreements (BIH orientation). The initial orientation at 1984.0 is the orientation given by the Bureau International de l'Heure (BIH) Terrestrial System (BTS84).

The GCRS specification (IAU Resolution A4, 1991, and update: IAU Resolution B1.3, 2000) follows a geocentric relativistic metric. The orientation of the GCRS is derived from the BCRS (IAU Resolution B2, 2006). The different metrics of GCRS and BCRS imply a slight difference of the respective orientations, which are called geodesic precession and geodesic nutation (Fukushima 1991).

The BCRS is assumed to be oriented according to the ICRS (IAU Resolution B2, 2006). The latter is recommended to show no global rotation with respect to a set of distant extragalactic objects. According to IAU Resolution B2 (1997) the initial orientation of the ICRS is given through the IERS celestial reference frame of the year 1995 (IERS95) as described by the ICRS Product Center (Arias et al. 1995) within the IERS.

Since the EOP depend on the actual realisations of the conventional terrestrial and celestial reference systems, the EOP system should be readjusted as soon as a new release of ITRF or ICRF is adopted.

Concerning its numerical realisation, the transformation of Cartesian coordinates from ITRS to GCRS at date t is split into three segments

$$\begin{tikzcd}
\text{ITRS} \arrow[dr, "W(t)", "\text{polar motion}"'] & & & \text{GCRS} \\
& \text{TIRS} \arrow[r, "R(t)", "\text{Earth rotation}"'] & \text{CIRS} \arrow[ur, "Q(t)", "\text{precession-nutation}"'] &
\end{tikzcd}$$

where $Q(t)$, $R(t)$, and $W(t)$ are rotation matrices and $R(t)$ fits to the mean physical rotation of the Earth. The meaning of "mean" still has to be specified. The choice of the intermediate systems Terrestrial Intermediate Reference System (TIRS) and Celestial Intermediate Reference System (CIRS) is delaminated by the convention on $R(t)$ being an elementary rotation around the z-axis. Hence TIRS and CIRS have a common z-axis, refering to the celestial pole, which approximates a mean rotation axis of the Earth. $Q(t)$ and $W(t)^{-1}$ represent the motion of that celestial pole in the GCRS and ITRS respectively. If the celestial pole is choosen according to the IAU 2000/2006 resolutions, it will be called Celestial Intermediate Pole (CIP).

According to IAU 2000 Resolution B1.7, the CIP separates the motion of the rotation axis of the ITRS in the GCRS into a celestial and a terrestrial part. The convention is such that (Capitaine 2013; Petit and Luzum 2010):

- The celestial motion of the Celestial Intermediate Pole (CIP) (precession-nutation) includes all the terms with periods greater than 2 days in the Geocentric Celestial Reference System (GCRS). According to this definition, precession-nutation of the CIP includes the Free Core Free Core Nutation (FCN) signal, but does not include the so-called subdiurnal nutations.
- The terrestrial motion of the CIP (polar motion) includes all the terms outside the retrograde diurnal band in the ITRS (i.e. frequencies lower than -1.5 cycles per sidereal day (cpsd) or greater than -0.5 cpsd).

As outlined in the IERS Conventions 2010 (Petit and Luzum 2010), the motion $Q(t)$ of the CIP in the GCRS is realised by the IAU 2006/2000A precession-nutation model (Wallace and Capitaine 2006) plus additional time-dependent corrections derived by the IERS from space geodetic techniques. The motion $W(t)^{-1}$ of the CIP in the ITRS is provided by the IERS through time series derived from space geodetic observations and models including variations with frequencies outside the retrograde diurnal band. The implementation of the IAU 2000 and IAU 2006 resolutions for the transformation is detailed in the IERS Conventions 2010 (Petit and Luzum 2010).

Concerning the realisation of EOP products, the EOP are represented by the five following quantities (as specified the latest IAU 2000/2006 version of the terrestrial-celestial transformation):

- $\delta X = X - X_{\text{model}},\ \ \delta Y = Y - Y_{\text{model}}:$ corrections to the x- and y-coordinates of the CIP unit vector in the celestial system GCRS using the model IAU 2000/2006,
- $\Delta\text{UT1} = \text{UT1} - \text{UTC}:$ difference of mean solar time (Universal Time UT1) and Coordinated Universal Time (UTC) vice the averaged atomic time,
- x_p, y_p: Cardan angles $W(t) = R_3(-s')R_2(x_p)R_1(y_p)$, called “pole coordinates”.

The IERS is responsible for providing the time series of x_p, y_p, ΔUT1, δX, δY on an operational basis derived from the various space geodetic techniques (VLBI, SLR, GNSS, and DORIS). The EOP products are available from the database of the IERS (see www.iers.org). Two Product Centers are responsible for the EOP generation, namely the IERS Earth Orientation Center and the IERS Rapid Service/Prediction Center (see IERS 2020). The IERS EOP series result from a combination of different input data provided by different space-geodetic techniques and the corresponding IAG Services, i.e., IDS, IGS, ILRS, and IVS.

In the IERS Conventions 2010, a conventional model for the mean pole is given. It consists of a third order polynomial until 2010.0, and a linear model later on. This model was replaced by a purely linear model (secular pole) in the February 2018 update of the conventions (IERS 2018). This update affects the modelling of displacements of reference points as well as the geopotential due to pole tide and ocean pole tide.

It should also be noted that besides the IERS EOP products, other combined Earth orientation series (e.g., SPACE 2018, COMB 2018, POLE 2018) are generated annually at JPL’s Geodynamics and Space Geodesy Group in support of tracking and navigation of interplanetary spacecraft (Gross 2000; Ratcliff and Gross 2019).

4.3.2 IERS Earth Orientation Center

The IERS Earth Orientation Center is responsible for monitoring of long-term EOP, publications for time dissemination and leap second announcements. It is located at the Observatoire de Paris in France (see hpiers.obspm.fr/eop-pc). The general procedure for the generation of the EOP series is described in various publications (e.g., Bizouard and Gambis 2009; Bizouard et al. 2019; Gambis 2004; Gambis and Luzum 2011).

The Earth Orientation Center provides the following main products:

Bulletin B contains final daily Earth orientation data for one month
(see ftp://hpiers.obspm.fr/iers/bul/bulb_new/bulletinb.pdf)

Bulletin C contains announcements of leap seconds in UTC
(see ftp://hpiers.obspm.fr/eoppc/bul/bulc/BULLETINC.GUIDE)

Bulletin D contains an announcement of the value $\Delta\text{UT1} = \text{UT1} - \text{UTC}$ (see ftp://hpiers.obspm.fr/eoppc/bul/buld/BULLETIND.GUIDE)

EOP 14C04 contains long term Earth orientation data
(see ftp://hpiers.obspm.fr/iers/eop/eopc04/C04.guide.pdf)

Realisation of EOP time series

The Earth Orientation Center of the IERS, located at Paris Observatory, SYRTE, has the task to provide the international reference time series for the EOPs, referred as "IERS C04", resulting from a combination of EOP series derived from the four space geodetic techniques VLBI, SLR, GNSS, and DORIS. The IERS EOP 14C04 (abbreviated 14C04) solution became the international reference EOP series on February 1, 2017 (Bizouard et al. 2019). It replaced the former IERS EOP 08C04 series (Bizouard and Gambis 2009). The 14C04 series is available from 1962 on and it provides updates until about 30 days in the past. It contains smoothed values of x_{p}, y_{p}, UT1–UTC, LOD, δX, δY at 1-day intervals w.r.t. IAU 2006/2000A precession-nutation model and it is aligned on the ITRF2014 and ICRF2. The 14C04 series is updated on a daily basis with a latency of 30 days and the data are accessible as yearly files since 1962 and as one file 1962–now. A documentation for this EOP series is given by Bizouard et al. (2019).

The generation of the 14C04 solutions is based on the combination of operational series as provided by the technique centres of IVS, ILRS, IGS, and IDS, as well as operational solutions maintained by several IVS analysis centres (including VLBI intensives) and one IGS analysis centre (Bizouard et al. 2019). Thus, in case of VLBI and GNSS, in addition to the intra-technique combined series also solutions of individual analysis centres are used for the 14C04 combination. While the three satellite techniques deliver continuous input data for estimating pole coordinates and LOD, VLBI provides the full set of all five EOP, but with non-continuous observations organised in VLBI sessions. In addition, also the EOP solution associated with the ITRF2014 is used as reference series to align the 14C04 solution with the latest realisation of the terrestrial reference frame.

The computation of the C04 series is split into two parts (Bizouard et al. 2019):

- In the initial part, the data preparation is performed once per year. This data preparation comprises the selection of input series, the rescaling of the formal uncertainties provided with the EOP values, and the characterisation of their eventual inconsistency with respect to the ICRF and ITRF.
- The second part is the combination procedure itself which is done on a daily basis. This procedure comprises several steps which are described in Bizouard et al. (2019).

The IERS Earth Orientation Center has upgraded the processing to align the 14C04 results with the ITRF2014 (Bizouard et al. 2017). By estimating and removing continuous piece wise linear functions from the intra-technique solutions over a period of 31 years (1984–2015) with respect to the guide series, namely the EOP solution associated with the ITRF2014 and the IVS combined series, the 14C04 results get rid of the so-called "network effect". This leads to an improved consistency and stronger long-term stability of the solution, which has been confirmed by Allan deviation analysis (Bizouard et al. 2017).

To assess the accuracy of the 14C04 solution various comparisons have been performed (Bizouard et al. 2019). A comparison with the former 08C04 series indicates a significant improvement of the EOP results. The y-pole component of the 08C04 series shows a jump of about 30 μas in 2011, which is not visible in the new 14C04 series. Also the noise level of the x- and y-pole components obtained from 14C04 could be reduced significantly compared to the previous 08C04 series. This is evidenced by the standard deviations of the differences between the C04 (both 08C04 and 14C04) and the intra-technique and guide series (see Table 6 in Bizouard et al. (2019)). The 14C04 differences to the IVS combination exhibit standard deviations of less than 30 μas for nutation and 3.4 μs for UT1 over the period 2010–2015. The differences to the pole coordinates of the IGS solution reveal a standard deviation of 30 μas for polar motion.

4.3.3 IERS Rapid Service/Prediction Center

The IERS Rapid Service/Prediction Center is responsible for providing predicted EOP and measured EOP on a rapid turnaround basis, primarily for real-time users and others needing EOP information sooner than that available in the final series published by the IERS Earth Orientation Center. It is located at the United States Naval Observatory (USNO) in Washington, D.C., USA (see www.usno.navy.mil/USNO/earth-orientation). The general procedure for the generation of the real-time EOP and predictions is described in various publications (e.g., Luzum et al. 2014; McCarthy and Luzum 1991; Stamatakos et al. 2020, 2007).

The IERS Rapid Service/Prediction Center provides the following main products:

Bulletin A contains x_{p}, y_{p} and UT1–UTC including their errors at daily intervals and predictions for one year into the future (see ftp://cddis.gsfc.nasa.gov/pub/products/iers/readme.bulla).

Standard Rapid EOP Data contain quick-look weekly estimates of the EOP since 1973-01-02 (`finals.all`) or since 1992-01-01 (`finals.data`) and predictions for the next 365 days (see ftp://cddis.gsfc.nasa.gov/pub/products/iers/readme.finals).

Daily Rapid EOP Data contain quick-look daily estimates of the EOP (file `finals.daily`) for the last 90 days and predictions for the next 90 days (see ftp://cddis.gsfc.nasa.gov/pub/products/iers/readme.finals).

GPS Daily Rapid EOP Data contain quick-look daily estimates of the EOP (file `gpsrapid.daily`) for the last 90 days and predictions for the next 15 days (see ftp://cddis.gsfc.nasa.gov/pub/products/iers/readme.gpsrapid).

Realisation of real-time EOP and predictions

The input data series for the IERS Rapid Service and Prediction Center along with estimated accuracies for each of these contributions to the EOP combination solutions are given in Table 1 of Stamatakos et al. (2020). These series include combined intra-technique solutions of the IVS, IGS and ILRS as well as VLBI, SLR and GNSS solutions of individual analysis centres. All the VLBI contributions provide direct measurements of UT1. The IGS ultra-rapid solutions (IGS Ultra) provide LOD as input parameter, and the solutions labelled as USNO GPS UT contain UT1-like estimates based on GPS orbit modelling. The IGS Final and IGS Rapid as well as the solutions of the ILRS only provide pole coordinates as input parameters. Due to orbit modelling issues of the satellite techniques and correlations between orbit parameters and the EOP, the VLBI solutions have been used to correct for an LOD bias and to minimise drifts in UT estimates in the IGS Ultra and the USNO GPS UT solutions.

The algorithm used for the determination of the quick-look EOP results is based on a smoothing cubic spline interpolation. Each of the input data is weighted according to their reported errors. The procedure is referred to as a "weighted smoothing cubic spline" (Luzum et al. 2014; McCarthy and Luzum 1991). The input series are corrected for possible systematic differences in the form of offsets and rates with respect to the long-term 14C04 series of the IERS Earth Orientation Centre by using a robust linear estimator. The statistical weights used in the spline are proportional to the inverse square of the estimated accuracy of the individual techniques computed over the past several years. Minimal smoothing is applied, consistent with the estimated accuracy of the input data. More information on the combination approach is provided in the literature (Luzum et al. 2014; Stamatakos et al. 2020).

The accuracy of the combined EOP solutions of Bulletin A is shown in Table 2 of Stamatakos et al. (2020). The mean and standard deviations are derived from a comparison of the running, weekly, and daily products compared to the long-term 14C04 series of the IERS Earth Orientation Center. The obtained standard deviations are in the range of about 40 to 80 μas for the pole coordinates and between 50 and 75 μs for UT1–UTC.

Concerning the prediction techniques, the algorithm for polar motion predictions was changed in 2017 to incorporate a least-squares, autoregressive (LS+AR) method as described in (Stamatakos et al. 2020). The UT1–UTC prediction makes use of UT1-like data product derived from a combination of the operational National Centers for Environment Prediction (NCEP) and US Navy's Global Environmental Model (NAVGEM) Atmospheric Angular Momentum (AAM) analysis and forecast. AAM-based predictions are used to determine the UT1 predictions for a prediction length up to 7.5 days (Johnson et al. 2005). For longer predictions, the LOD excitations are combined smoothly with the longer-term UT1 predictions as described by McCarthy and Luzum (1991).

Table 4.4 summarises the quality of the predictions of the pole coordinates and UT1–UTC until 90 days in the future (Stamatakos et al. 2020). The RMS values of the differences between the EOP time series predictions produced by the 17:00 UTC daily EOP solutions and the 14C04 solution demonstrate that the accuracy of the predictions could be significantly improved due to the implementation of refined procedures.

Table 4.4: Root mean square of the differences between the EOP time series predictions produced by the 17:00 UTC daily EOP solutions and the 14C04 combination solutions for 2017 (the values are extracted from Table 3a of Stamatakos et al. (2020)).

Days in future	x_p mas	x_p mas	UT1–UTC ms
0	0.07	0.04	0.074
1	0.31	0.23	0.087
5	1.75	1.32	0.198
10	3.29	2.29	0.537
20	5.89	3.80	2.347
40	10.24	5.78	5.118
90	17.25	9.28	9.748

4.3.4 Discussion of the present status

Theoretical aspects of precession-nutation models

In 2015, IAU and IAG established a Joint Working Group (JWG) "Theory of Earth rotation and validation" that continued the former IAU/IAG JWG "Theory of Earth Rotation" (Ferrándiz and Gross 2015). During the current term, the JWG is continuing under the name "Improving Theories and Models of the Earth's Rotation". The purpose of this JWG is to promote the development of theories of Earth rotation that are fully consistent and that agree with observations, useful for providing predictions of the EOP with the accuracy required to meet future needs as recommended by GGOS. From the findings of this JWG, it can be concluded that various issues are affecting the accuracy and consistency of the presently available precession-nutation models. The work provided the basis for the formulation of

IAG resolution No. 5 (2019) "Improvement of the Earth's Rotation Theories and Models" (see Section 1.2.4). The issues of precession-nutation models have been discussed during the Unified Analysis Workshop 2019 in Paris, and several recommendations have been provided (Ferrandiz and Escapa 2019; Gross et al. 2019). A summary of these recommendations is given at the end of this section. More information on this JWG is available at the website hosted by the University Alicante at web.ua.es/en/wgterv/.

Input data for EOP generation

The EOP products provided by the Earth Orientation Center and the Rapid Service/Prediction Center of the IERS are generated from VLBI, SLR, GNSS data. For the latest 14C04 series also DORIS data have been included for the first time. The input data comprise intra-technique combined solutions provided by the technique centres of the IVS, ILRS, IGS, and IDS, as well as individual analysis centre solutions and the EOP solution associated with the ITRF2014 for the alignment with the ITRS. As a consequence, several measurements of the same space geodetic technique are included more than once in the EOP combination. At the same time, the corresponding stochastic model does not account for the multiple usage of identical input data leading to over-optimistic formal errors.

Although the standards and conventions used by all the contributing AC should follow the IERS Conventions as closely as possible, the current status is that they are not always fully (or clearly) documented, and that in some cases the corresponding AC log files are not up to date. Thus, it is difficult to assess the impact of inconsistencies on the EOP products.

Combination methods and consistency of EOP products

The combination procedure for the generation of the 14C04 series comprises several processing steps, which are performed on the solution (parameter) level. Regarding the contributing input solutions, only VLBI contains the full set of EOP, whereas the satellite techniques provide the pole coordinates and LOD. By using these data sets, not all correlations among the EOP can be considered in the combination, and in addition the parametrisations of the EOP are not fully consistent across the different techniques. Thus, the procedure of the IERS Earth Orientation Centre cannot be considered as a rigorous combination approach. Moreover, the literature gives a rather general description of the various data preparation and processing steps for the generation of the 14C04 series, whereas the analytical/mathematical combination model (including the alignment and extrapolation of the series) is not fully described. Thus, it is difficult to judge the present combination procedure comprehensively and for assessing their impact on the combination results.

The procedure applied at the IERS Rapid Service/Prediction Center for the generation of the real-time EOP and predictions cannot be considered as a rigorous combination, since it is also based on various processing steps on the solution (parameter) level. Although the general procedure is described in the literature, a detailed documentation of the analytical and mathematical foundations is partly missing. It was reported by Stamatakos et al. (2017), that beginning in 2016, a UT1–UTC convergence solution problem was occurring more often than in previous years. It was found that a probable cause could be the UT GPS inputs or the pre-processing of these input data before using it in the combination.

As described in Bizouard et al. (2019), the 14C04 solution has been tied to the two guide series, the IVS combination and the EOP solution associated with the ITRF2014, to ensure the consistency with the conventional reference frames, the ICRF2 and ITRF2014. However, this procedure does not include all relevant parameters of the contributing space techniques, and thus, it does not ensure full consistency between the EOP and the terrestrial and celestial reference frame.

4.3.5 Interaction with other products

The Earth Orientation Parameter are directly linked with

- Celestial reference frames
- Terrestrial reference frames
- Second degree gravity field coefficients (C_{20}, C_{21}, S_{21})
- Satellite orbits
- Parameters of geophysical fluids, particularly atmospheric, oceanic and hydrologic angular momentum (AAM, OAM, HAM).

4.3.6 Open problems and recommendations

Theoretical aspects of precession-nutation models

Issues affecting the accuracy and consistency of the presently available precession-nutation models were addressed by the joint IAU/IAG Working Group (JWG) "Theory of Earth rotation and validation" that continued the former JWG "Theory of Earth Rotation" (Ferrándiz and Gross 2015). Some of the major findings of this JWG was presented at the Unified Analysis Workshop (Ferrandiz and Escapa 2019). The following recommendations were provided at this Workshop (Gross et al. 2019): (1) the amplitudes of the leading nutations of the IAU2000 theory be updated and a shortened series for certain operational purposes be tested; (2) the inconsistencies found in the precession-nutation models be corrected; (3) the available FCN models be tested (for fitting Celestial Pole Offset (CPO)) and consideration be given to the question of whether or not the IERS should recommend the FCN models to use; and (4) the tasks of the joint IAU/IAG Working Group on Improving Earth Rotation Theories and Models be prioritised to get outcomes in two years.

Input data for EOP generation

In order to get consistent EOP products, it is a fundamental requirement that the input data must be based on unified standards, conventions and models. This objective is the basis for the following recommendations:
(1) Although the contributions used for the generation of the EOP products should be based on the latest version of the IERS Conventions, it is not clear if there are any deviations. Thus, all the geometric services (IGS, ILRS, IVS, and IDS) together with their contributing analysis centres should provide the relevant information on the present status of the standards and conventions currently applied in the data processing.
(2) The subsequent change of the mathematical representation of EOP functions in solutions or normal equations can involve a considerable loss of approximation accuracy. Thus, the parameterisation of the EOP functions should be identical for the contributions of all individual space geodetic techniques.
(3) Though VLBI only allows to solve for the full set of EOP, the satellite techniques should provide solutions or equations containing all five EOP regardless of whether some of them were fixed or constrained. That makes the full information contained in the different space techniques available for the combination, which is necessary to derive realistic correlations between the parameters.
(4) Moreover, the measurements of a single space geodetic technique should only be included once in the EOP combination in agreement with the associated stochastic model.
(5) It is also recommended to investigate all the contributing input data in detail to avoid any data problems or inconsistencies in the EOP combinations.
(6) At the Unified Analysis Workshop 2019 (Gross et al. 2019), it was recommended that also LLR data should be considered for the EOP combinations.

Combination methods and consistency of EOP products

A reference paper for the generation of the 14C04 has been provided by Bizouard et al. (2019). The procedures for the determination of the near-real time and predicted EOP are mainly described in the IERS Annual Reports (Stamatakos et al. 2020). It is recommended that the analytical and mathematical foundations of the EOP combination procedures are described in full detail. This holds also for the alignment of the long-term series with the terrestrial and celestial reference frame as well as for the extrapolation of the EOP beyond the ITRF2014 data period. The IERS Earth Orientation Center and the IERS Rapid Service/Prediction Center should consider a detailed description of the procedures including the full mathematical and analytical background in IERS Technical Notes (in the same way as for the ITRF).
Although the accuracy of both, the 14C04 series and the near real-time and predicted EOP has been improved due to advanced procedures, it is recommended that the EOP Product Centers should consider the implementation of rigorous combination methods. Concerning EOP predictions, it should be investigated how the results could be further improved by reducing the latency of the last data point and by more frequently updating the AAM and Oceanic Angular Momentum (OAM) data.

Concerning the accuracy of the 14C04 series, the estimates published in the literature (Bizouard et al. 2019) are derived from an internal comparison, and are certainly too optimistic. Thus, it is recommended to use also external data and geophysical models for an accuracy assessment of the EOP products. Another topic is the consistency of the ICRF, the ITRF and the EOP (see IUGG resolution No. 3 (2011) and IAG resolution No. 2 (2019)) which has been addressed in Section 4.1 (see Recommendation 1.4).

Summary of recommendations on EOP

Recommendation 3.1 : Review of precession-nutation models: As outcome of the Unified Analysis Workshop 2019, the following recommendations were provided (Ferrandiz and Escapa 2019): (1) update the amplitudes of the leading nutations of the IAU2000 theory and test shortened series for certain operational purposes; (2) correct the inconsistencies found in the precession-nutation models; (3) test the available FCN models and consider whether the IERS should recommend FCN models or not. (4) The IAU/IAG JWG on Improving Earth rotation theories and models should prioritise these tasks to get outcomes in two years.

Recommendation 3.2 : Input data for EOP products: complete and up-to-date documentations of the standards and conventions for the contributing input solutions are necessary. Remaining inconsistencies need to be resolved to ensure consistent EOP products. The weighting should be properly performed if measurements of the same space geodetic technique are included more than once in the EOP combination.

Recommendation 3.3 : EOP combination procedure: The general procedures for the EOP combinations are described in the literature. It is recommended that also the analytical and mathematical foundations are described in full detail, which probably could be done in an IERS Technical Note. Furthermore, the development of rigorous combination methods should be considered by the EOP Product Centers.

Recommendation 3.4 : EOP Prediction: Although the accuracy has been improved significantly by implementing refined procedures it should be investigated how the results can be further improved by reducing the latency of the last data point and by more frequently updating the AAM and OAM data.

4.4 GNSS satellite orbits

Global Navigation Satellite Systems (GNSS) like the US American GPS, the Russian GLONASS, the European Galileo, and the Chinese BeiDou are the most popular space geodetic techniques with a wide range of applications. Precise GNSS satellite orbits and clocks provide the basis for mm-level positioning for realising global and regional reference systems, geophysical studies, surveying, deformation monitoring, and cadastre.

The Analysis Centres (ACs) of the IGS process observations of global GNSS tracking networks on a regular basis in order to provide a variety of products. One of the IGS core products are the final orbits. GPS and GLONASS final orbits are generated by the IGS Analysis Centre Coordinator (ACC) as a weighted mean of the individual AC orbits (Beutler et al. 1995; Griffiths and Ray 2009). They are provided with a latency of 12 – 18 days.

For the two new global navigation systems, Galileo and BeiDou, and the regional Quasi-Zenith Satellite System (QZSS), satellite orbits are computed by the ACs of the Multi-GNSS Pilot Project (Montenbruck et al. 2017b) of the IGS. The Indian Regional Navigation Satellite System (IRNSS) is currently not covered by the MGEX ACs due to lack of dual-frequency tracking data. An experimental multi-GNSS orbit product is generated by the IGS ACC since April 2019 covering GPS, GLONASS, Galileo, BeiDou, and QZSS (acc.igs.org/mgex_experimental.html).

Due to advances in observation modelling and processing strategies since the establishment of the IGS in 1994, the orbit quality has steadily improved. In order to achieve the highest product quality also for the orbits of the early years and to achieve consistency with current operational orbits, the IGS conducted two reprocessing campaigns up to now. The second reprocessing covers 1994 – 2014 (Griffiths 2018) and provided the input for ITRF2014 (Altamimi et al. 2016). The third reprocessing campaign is currently in progress and will provide input for ITRF2020. Users are advised to use the latest generation of reprocessed products to achieve the highest level of accuracy as well as consistency with the operational products for time periods where the reprocessed products are not available.

The individual analysis centres contributing to the IGS final orbit combination are:

- **COD** Center for Orbit Determination in Europe, Switzerland
- **EMR** Natural Resources Canada, Canada
- **ESA** European Space Agency, Germany
- **GFZ** Deutsches GeoForschungsZentrum, Germany
- **GRG** GRGS-CNES/CLS, France
- **JPL** Jet Propulsion Laboratory, USA
- **MIT** Massachusetts Institute of Technology, USA
- **NGS** National Geodetic Survey, USA
- **SIO** Scripps Institution of Oceanography, USA

4.4.1 Summary of standards

The standards listed in Table 4.5 are based on the recommendations for the second and third IGS reprocessing campaign (acc.igs.org/reprocess2.html and acc.igs.org/repro3/

Table 4.5: Selected standards of the third IGS reprocessing campaign.

General Standards	IERS 2010 Conventions (Petit and Luzum 2010)
Reference Frame	ftp://igs-rf.ign.fr/pub/IGSR3/IGSR3_2077.snx
Antenna Model	http://ftp.aiub.unibe.ch/users/villiger/igsR3_2077.atx
P1C1 Code Biases	ftp://ftp.unibe.ch/aiub/bcwg/cc2noncc
Phase Wind-Up	according to J. Wu et al. (1993)
Gravity Field	e.g., GGM05C (Ries et al. 2016)
Ocean tide model	FES2014b (Carrere et al. 2015)
Pole tide	linear mean pole (IERS 2018)
Subdaily ERP Model	Desai and Sibois (2016)
Earth radiation pressure	applied, http://acc.igs.org/orbits/ERPFBOXW.F
Antenna thrust	applied (Steigenberger et al. 2018, 2019)
Non-Tidal Loading	not applied
Higher-order Ionosphere	2nd and 3rd order applied (Fritsche et al. 2005; Hernández-Pajares et al. 2011)
A Priori Troposphere Delay	GPT2 model (Lagler et al. 2013) to compute hydrostatic delays according to Davis et al. (1985)
Troposphere Mapping	GPT2 (Lagler et al. 2013) or more modern

repro3.html) as well as the recommendations of the IGS Analysis Center Workshop 2019 and the Unified Analysis Workshop 2019 (acc.igs.org/workshop2019.html and www.ggos.org/en/unified-analysis-workshop-2019/general-uaw/). For the third IGS reprocessing, the IGS Reference Frame Working Group and the Antenna Working Group prepared dedicated reference frame and antenna calibration files, see Table 4.5. Due to mostly outdated analysis log files, the compliance of the ACs with these standards could not be verified.

4.4.2 Discussion and deficiencies

Solar radiation pressure modelling

Modeling of the Solar Radiation Pressure (SRP) is probably the largest error source of today's GNSS orbits. Deficiencies in the SRP modelling are visible as harmonics of the draconitic year in orbital (Griffiths and Ray 2013) and other parameters: station positions (Amiri-Simkooei 2013; Ray et al. 2008), geocentre (Hugentobler et al. 2005), and Earth Rotation Parameters (ERP) (Steigenberger 2009). A comparison of different SRP models can be found in Sibthorpe et al. (2011).

A partly reduction of these systematic errors was achieved by recent developments including an adjustable box-wing model (Rodriguez-Solano et al. 2014), the extended Empirical CODE Orbit Model (Arnold et al. 2015), a cuboid box model for the Galileo IOV satellites (Montenbruck et al. 2015b), a box-plate model for GIOVE-B (Steigenberger et al. 2015), and box-wing models for Galileo (Bury et al. 2019), BeiDou (X. Yan et al. 2019), and QZS-1 (Montenbruck et al. 2017a; Zhao et al. 2018a). The ray-tracing approach is the most sophisticated SRP modelling technique (Bhattarai et al. 2019; Darugna et al. 2018; Z. Li et al. 2018) but requires detailed knowledge about geometry and optical properties. Optical properties and surface areas are currently available for GPS Block II (Fliegel et al. 1992), Block IIR (Fliegel and Gallini 1996), Galileo IOV and FOC satellites (GSA 2019), and the QZS-1 – 4 satellites (Cabinet Office 2019a,b,c,d). Incomplete optical properties (only absorption coefficients) and surface areas are available for BeiDou-2 (CSNO 2019b) and BeiDou-3 (CSNO 2019a). However, no public information on the detailed geometry of any GNSS satellites is currently available.

Table 4.6 lists orbit models recommended for different satellite types included in the third IGS reprocessing. Depending on the satellite type, different versions of the Empirical CODE Orbit Model (ECOM, Arnold et al. 2015; Beutler et al. 1994) or the GPS Solar Pressure Model (GSPM, Bar-Sever and Kuang 2005) are recommended as a minimum modelling standard. However, applying a bow-wing model together with additional empirical parameters is preferred.

Earth radiation pressure

Earth radiation pressure due to visible and infrared emissions of the Earth in particular affects the scale of the orbits (Bury et al. 2020; Rodriguez-Solano et al. 2011; Ziebart et al. 2007). Starting with the switch to IGS14/igs14.atx, Earth radiation pressure is considered by most ACs. Whereas optical properties of satellite surfaces for visible light are available for several satellites as mentioned in the previous section, coefficients for infrared radiation are not yet available.

Antenna thrust

When transmitting navigation signals, GNSS satellites experience an acceleration in radial direction depending on the power of the emitted signals called antenna thrust. Rodriguez-Solano et al. (2012) report a 5 mm radial orbit change when considering antenna thrust in GPS orbit determination.

Steigenberger et al. (2018) measured the transmit power of selected GPS, GLONASS, Galileo, and BeiDou-2 satellites with a high-gain antenna. They report transmit power values between 20 and 265 W resulting in radial orbit shifts between 1 and 27 mm. Manufacturer values for the transmit power of the QZSS satellites are published in (Cabinet Office 2019a,b,c,d). Recent transmit power measurements of newly launched GLONASS satellites are given in Steigenberger et al. (2019). Due to the lack of transmit antenna gain pattern, the BeiDou-2 gain pattern were

Table 4.6: Orbit modelling recommendations for the third IGS reprocessing campaign according to Moore (2019).

Satellite type	Minimum modelling	Preferred modelling
GPS Block IIA	ECOM-2, GSPM	Box-wing + empirical
GPS Block IIR	ECOM-2, GSPM	Box-wing + empirical
GPS Block IIF	ECOM-1, GSPM	Box-wing + empirical
GPS Block III	ECOM-2, GSPM	Box-wing + empirical
GLONASS	ECOM-1, GSPM(GLONASS)	Box-wing + empirical
Galileo	ECOM-2	Box-wing + empirical

used for estimation of the BeiDou-3 MEO satellite transmit power included in the IGS satellite metadata file available at mgex.igs.org/IGS_MGEX_Metadata.php. The transmit power of the BeiDou-3 IGSO and GEO as well as all IRNSS satellites is currently unknown.

Attitude

The basic attitude condition of a GNSS satellite is that the navigation antenna points to the centre of the Earth and the solar panels are oriented perpendicular to the Sun (Montenbruck et al. 2015a). To fulfill these conditions, the satellite has to rotate around its z-axis. The speed of this rotation depends on the elevation of the Sun above the orbital plane. Due to technical restrictions, the implementation of the attitude control deviates from this ideal case. Several models for the attitude of dedicated GNSS satellites are available but these models are not used by all ACs at the moment.

- GPS Block II, IIA, IIR: Kouba (2009a)
- GPS Block IIA: Rodriguez-Solano et al. (2013)
- GPS Block IIF: Dilssner (2010)
- GLONASS-M: Dilssner et al. (2010)
- BeiDou-2 IGSO-1, IGSO-6, MEO-6: Dilssner (2017)
- BeiDou-3S: X. Li et al. (2018)
- BeiDou-3: CSNO (2019c) and Shanghai Engineering Center for Microsatellites (2018)
- Galileo IOV and FOC satellites: GSA (2019)
- QZSS: Cabinet Office (2019a,b,c,d).

Satellite antenna model

GNSS measurements refer to the electrical phase centre of the transmission and receiving antennas. The mean differences between the mechanically well-defined antenna reference point of the receiver antennas and the centre of mass for the satellite antennas are called Phase Centre Offsets (PCOs). Variations of the actual phase centre depending on azimuth and elevation of the transmitted/received signal are called Phase Centre Variations (PCVs). As no ground calibrations are available for the transmitting antennas of GPS and GLONASS except for the first GPS III satellite (G074), satellite antenna phase centre offsets and variations were estimated from global GNSS data to derive antenna models for these systems.

For GPS and GLONASS, the current model `igs14.atx` (Rebischung et al. 2016) contains only block-specific PCVs and satellite-specific PCOs for the ionosphere-free linear combination of L1 and L2. Azimuthal variations of the satellite antennas (Schmid et al. 2005) are not yet considered for these GNSS. Furthermore, satellite-specific antenna PCVs could account for deviations of the individual transmitting antennas from the block-specific mean values. Such satellite-specific PCVs are published for each transmit frequency of Galileo IOV and FOC (GSA 2019) as well as QZS-2 – 4 (Cabinet Office 2019b,c,d).

Lockheed Martin published L1, L2, and L5 PCO values for the first GPS III satellite (Lockheed Martin 2019). L5 satellite antenna calibrations for the other GPS satellites as well as GLONASS L3 calibrations are currently not available. Manufacturer PCO values for the BeiDou-3S satellites are given in (Zhao et al. 2018b). Frequency-specific satellite antenna phase centre offsets of the active BeiDou-2 and BeiDou-3 satellites for B1, B2, and B3 were published by the China Satellite Navigation Office (CSNO) in December 2019.

The availability of pre-flight calibrations for the Galileo satellite antennas makes it possible to derive the terrestrial scale from GNSS observations. The inclusion of Galileo in the third IGS reprocessing might even enable a contribution of GNSS to the scale definition of ITRF2020 (Villiger et al. 2019).

Receiver antenna model

The IGS receiver antenna model is mainly composed of absolute robot calibrations for L1 and L2. Only for a few antennas, converted relative calibrations are included. For the third IGS reprocessing campaign, a dedicated file IGSR3_2077.atx was compiled by the Antenna Working Group including 36 robot calibrations by Geo++ and one chamber calibration by University of Bonn for the following additional frequencies:

1176.45 MHz:	GPS L5, Galileo E5a, BeiDou B2a
1191.795 MHz:	Galileo AltBOC and BeiDou ACE-BOC
1207.14 MHz:	Galileo E5b, BeiDou B2b
1268.52 MHz:	BeiDou B3
1278.75 MHz:	Galileo E6, QZSS L62

However, not all frequencies are available for all calibrations. In addition, calibrations for GLONASS L3 (1202.025 MHz) and the IRNSS S-band frequency of 2492.028 MHz are still missing. The latter fact is insignificant at the moment as none of the antennas currently used within the IGS has a dedicated S-band capability and only one receiver type supports tracking of this signal.

Non-tidal loading

It is currently not recommended to apply non-tidal loading corrections at the observation level. However, aliasing effects can be introduced by this procedure (Dach et al. 2011). In addition, one should be aware that atmospheric loading is partly compensated when using GMF/GPT (Kouba 2009b; Steigenberger et al. 2009).

Subdaily ERP model

Griffiths and Ray (2013) found subdaily alias errors in IGS orbit, coordinate, geocentre, and ERP products. They attributed these errors to deficiencies of the IERS subdaily ERP model and concluded that an improved model is needed to mitigate these errors. As a consequence, an IERS Working Group on Diurnal and Semi-diurnal EOP Variations was established. In July 2019, this working group recommended the model of Desai and Sibois (2016) based on hydrodynamic ocean models obtained from altimetry.

Thermal modelling of monuments

Temperature changes induce thermal expansions of the bedrock and the monuments, where the GNSS antennas are mounted on, as well as tilts of the monuments. Romagnoli et al. (2003), H. Yan et al. (2009), Hiroshi (2013), Wang et al. (2018) report vertical displacements in the order of a few millimeters. However, as additional information about the thermal properties of the bedrock and the monument as well as temperature data are required, these corrections are currently not applied by the IGS ACs.

Operational information

The knowledge about selected operational information, in particular orbit maneuvers and attitude mode switches, is essential for precise orbit determination. Most GNSS providers issue so-called notice advisories announcing, e.g., planned outage periods of individual satellites:

GPS	Notice Advisory to NAVSTAR Users (NANU)
GLONASS	Notice Advisory to GLONASS Users (NAGU)
Galileo	Notice Advisory to Galileo Users (NAGU)
QZSS	Notice Advisory to QZSS Users (NAQU)

However, these advisories do not contain information about the exact maneuver epoch(s). Such information is currently only provided for QZSS by Cabinet Office, Government of Japan (CAO) in the form of detailed Operational History Information (OHI), i.e., time, duration, and magnitude of orbit maintenance maneuvers, changes of attitude modes, and time of reaction wheel unloading (Cabinet Office 2019e, 2020a,b,c).

Satellite metadata

Many of the effects and models described in the paragraphs above require knowledge about the corresponding GNSS satellites, e.g., satellite mass, sensor offsets, transmit power, etc. The IGS Multi-GNSS Working Group (MGWG) prepared an extension of the SINEX format in order to store and exchange these GNSS metadata (mgex.igs.org/IGS_MGEX_Metadata.php). The MGWG also maintains a draft release of the IGS satellite metadata file available at mgex.igs.org/igs_metadata.snx. More details on the importance and availability of satellite metadata are given in a white paper of the MGWG (Montenbruck and Steigenberger 2020).

4.4.3 Links to other products

Changes in the orbit modelling directly affect the following geodetic products:

- Terrestrial Reference Frame (TRF)
- TRF densification, e.g., regional reference frame of the IAG Reference Frame Sub-Commission for Europe (EUREF), or Sistema de Referencia Geocéntrico para las Américas (Geocentric Reference Frame for the Americas) (SIRGAS)
- GNSS satellite orbits and clocks
- Earth Orientation Parameters (EOP)
- Time-dependent Total Electron Content (TEC) maps
- Troposphere Zenith Total Delay (ZTD) time series

Changes in the orbit modelling affect the following products utilizing GNSS satellite orbits:

- Low Earth Orbiter (LEO) satellite orbits
- Static gravity field
- Time-dependent gravity field
- Time series of sea surface heights
- Time series of ice sheet and glacier elevations

4.4.4 Open problems and recommendations

The BPS has identified open problems in the field of GNSS orbit modelling and recommendations for further studies. These include:

- The consistency of the orbit solutions submitted by the IGS Analysis Centers has to be assured.
- Radiation pressure modelling and aliasing of orbital errors into geodetic parameters needs to be further studied.
- The impact of different arc lengths (1-day vs. 30 hours vs. 3-day) on geodetic parameters needs to be assessed. Selected aspects are already published in (Lutz et al. 2016)
- Receiver antenna calibrations beyond L1/L2 are required for *all* antennas and *all* frequencies used in the IGS.
- Satellite antenna offsets are required for IRNSS and SBAS satellites.
- Satellite antenna phase centre variations are required for BeiDou, IRNSS, QZS-1, and SBAS.
- Attitude models are required for GPS III, IRNSS, and SBAS satellites.
- Transmit power levels are required for GPS III, IRNSS, and SBAS satellites.
- No combined clock product is available for GLONASS, BeiDou, Galileo, and QZSS.
- No orbit products are available for IRNSS and SBAS.

Summary of recommendations on GNSS orbits

Recommendation 4.1 : Up-to-date analysis strategy summary files should be provided by all ACs for their operational, MGEX, and reprocessed products.

Recommendation 4.2 : The impact of analysis strategies such as radiation pressure modelling and orbit arc length on derived geodetic parameters should be investigated in detail.

Recommendation 4.3 : The contribution of Galileo antenna calibrations to a GNSS-derived realisation of the terrestrial scale should be studied.

Recommendation 4.4 : Satellite operators should be urged to provide missing detailed information about satellite dimensions, optical and infrared surface properties, attitude models, antenna offsets, antenna phase patterns, radio emission power, transmit antenna gain pattern, and operational information such as maneuvers.

Recommendation 4.5 : A multi-GNSS-capable orbit and clock combination software shall be developed.

4.5 Gravity and geoid

Gravity and geoid related data and products are collected and prepared by several IAG services, which all together are organized under the umbrella of the International Gravity Field Service (IGFS). The overall goal of IGFS is to coordinate the collection, validation, archiving and dissemination of gravity field related data and to coordinate courses, information materials and general public outreach relating to the Earth's gravity field. One of the overarching goals of the IGFS is to unify gravity field related products for the needs of the Global Geodetic Observing System (GGOS). IGFS coordinates the servicing of the geodetic and geophysical communities with gravity field-related data, software and information. The combined data of the IGFS entities include global models of the static (mean) Earth gravity field and its time-variable component, terrestrial, airborne, satellite and marine gravity observations, Earth tide data, Global Positioning System (GPS) levelling data, digital models of terrain and bathymetry as well as the oceanic gravity field and geoid from satellite altimetry.

Under the umbrella of the IGFS the following services and centres are available. They represent the "operating arms" of the IGFS and are independently organized. Nevertheless the IGFS coordinates their activities specifically regarding joint standards and conventions in order to ensure inter-operability of their products. In addition the IGFS Central Bureau (IGFS CB) develops and provides online applications for the creation of metadata for gravity and geoid data. This shall ensure that all metadata required to fully describe a numerical dataset are available.

BGI Bureau Gravimétrique International, Toulouse, France : The overall task of BGI is to collect, on a worldwide basis, all measurements and pertinent information about the Earth gravity field, to compile them and store them in a computerized data base in order to redistribute them on request to a large variety of users for scientific purposes.

ISG International Service for the Geoid, Milano, Italy : The main tasks of ISG are to collect geoid data on a worldwide scale, to collect and distribute software for geoid determination, to conduct research on procedure for geoid determination, to organize geoid schools, and to edit and distribute the Newton's Bulletin.

ICGEM International Center for Global Earth Models, Potsdam, Germany : The main tasks of ICGEM are to collect and archive all existing global gravity field models, web interface for getting access to global gravity field models, web based visualization of the gravity field models, their differences and their time variation, web based service for calculating different functionals of the gravity field models, web site for tutorials on spherical harmonics and the theory of the calculation service.

COST-G International Combination Service for Time-variable Gravity Fields, Bern, Switzerland :
COST-G is the Product Center of the IGFS for time-variable gravity fields. COST-G provides consolidated monthly global gravity models in terms of spherical harmonic coefficients and thereof derived grids by combining solutions from individual analysis centres (ACs). The COST-G ACs adopt different analysis methods but apply agreed-upon consistent processing standards to deliver time-variable gravity field models, e.g. from
GRACE/GRACE-FO,
low-low satellite-to-satellite tracking (ll-SST),
high-low satellite-to-satellite tracking (hl-SST),
Satellite Laser Ranging (SLR).

IDEMS International Digital Elevation Model Service, ESRI, Los Angeles, USA :
The main tasks of IDEMS are the distribution of data and information about Digital Elevation Models, relevant software and related datasets (including representation of Inland Water within Digital Elevation Models) which are available in the public domain.

IGETS International Geodynamics and Earth Tide Service, Strasbourg, France : The primary objective of IGETS is to provide a service to monitor temporal variations of the Earth gravity field through long-term records from ground gravimeters, tiltmeters, strainmeters and other geodynamic sensors. IGETS continues the activities of the GGP to provide support to geodetic and geophysical research activities those of ICET in collecting, archiving and distributing Earth tide records.

The general character of the products offered by the IGFS services is slightly different to products of other IAG services. While for example the ITRF is generated by a combination of products or observations provided by various other IAG services, IGFS products are mostly singular products either representing observations or geophysical models. Geophysical models usually are based on various data or observations, which are taken from a number of sources (e.g. satellite mission data, terrestrial observations). This implies that products from the IGFS as a minimum shall indicate the standards applied for their generation. In many cases this can be guaranteed, but there are also other products for which this hardly is possible. Often huge software packages, following specific standards and conventions implemented at some point form the basis for generating the products. These standards and conventions often are unknown or not specified together with the products.

In the following sections the products offered by the IGFS centres are shortly described and references for these products are provided. In the subsequent table for each identified product an inventory of the standards needed to describe these products is given (on a best knowledge basis). This information is extracted from the available information provided on the services web sites or the related documentation.

4.5.1 IGFS – Central Bureau

The IGFS Central Bureau (IGFS CB) acts as the central coordination and communication centre of the IGFS. The IGFS CB high level tasks include

- The provision of the link between the IGFS entities, IAG, and external projects, networks or organisations (oceanic, atmospheric, hydrology and others).
- The provision of the link to the GGOS bureau and communicate their requirements and recommendations to the IGFS.
- The implementation of standards and recommendations related to gravity field observations, securing consistency with geometric standards, and promotion of their use within the geoscientific community.

Within these activities the IGFS CB is developing online applications for the creation of metadata for gravity and geoid data, which shall be established as a service for searching the metadata database in order to locate dataset sources. In addition the metadata description secures that for a numerical dataset all needed information is available in order to correctly interpret it. So far draft versions for a geoid metadata editor and for a gravity data editor have been developed as Web applications. These metadata editors ask for the following information classes : **Geoid Metadata Editor** (v0.1.3) and **Gravity Metadata Editor** (v0.2.6).

Section 1: Metadata Reference Information

- Responsible Organisation and Contact
- Metadata Creation and Review Dates
- Metadata Prototype Information:

Section 2: Identification Information

- Resource Coordinate Reference System
- Resource Citation
- Resource Description
- Resource Status
- Resource Point of Contact
- Spatial Extent Geographic Bounding Box Coordinates
- Resource Maintenance and Updates
- Keywords
- Resource Constraints and Security Information

Section 3: Distribution Information

- Distributor
- Standard Order Process
- Metadata Constraints

Section 4 – Alternative Geoid Data: Standard and Conventions

- General Standards and Conventions (GM, a, f)
- Tide System
- Reference Ellipsoid
- Standard Density of the Earth

Page 4 – Alternative Gravity Data: Standard and Conventions

- General Standards and Conventions (GM, a, f, normal gravity reference ellipsoid)
- Earth's Gravity Field Permanent Tide System
- Earth Orientation Parameters Specifications
- Tidal Conventions
- Station Coordinates and Corrections

Section 5 – Alternative Geoid Data: Data and Data Quality Information

- Attribute Accuracy
- Logical Consistency Report
- Completeness Report
- Data Distribution
- Geoid Data / Gravity Data
- Position Accuracy / Position and Height Accuracy

Section 5 – Alternative Gravity Data: Data and Data Quality Information

- Attribute Accuracy
- Logical Consistency Report

- Completeness Report
- Data Distribution
- Gravity Data
- Position and Height Accuracy
- Time Period of Content

4.5.2 BGI – Bureau Gravimétric International

The overall task of the Bureau Gravimétrique International (BGI) is to collect, on a worldwide basis, all measurements and pertinent information about the Earth gravity field, to compile them and store them in a computerized data base in order to redistribute them on request to a large variety of users for scientific purposes. BGI central office is located in Toulouse, France, in the premises of the Observatoire Midi-Pyrénées (OMP).

The products of the BGI are

Gravity Databases:

- Collection of land and marine gravity data.
- Gravity data at reference stations.
- Data from absolute gravity stations (see mirror site: agrav.bkg.bund.de).

Grids and Models:

- High resolution grids and maps of the Earth's gravity anomalies (Bouguer, isostatic and surface free-air), computed at global scale in spherical geometry (World Gravity Map (WGM)2012).
- Regional gravity anomaly grids computed from the Earth Gravitation Model 2008 (EGM 2008).
- Gridded estimates of (i) gravity accelerations, (ii) gravity disturbances, (iii) quasigeoid undulations, and (iv) deflection of the vertical components from the ultra high resolution GGMplus global gravity field model (Hirt et al. 2013).

More details about tasks and products can be found at the service web site bgi.omp.obs-mip.fr/ and in the following documents offered via the web site:

- Land gravity data format (EOL) / Sea gravity data format (EOS): bgi.omp.obs-mip.fr/content/download/720/4949/file/BGI_EOL_EOS_Data_format.pdf
- Fortran routine to extract [Longitude/Latitude/Bouguer] fields from EOL data file: bgi.omp.obs-mip.fr/content/download/721/4952/file/conveol2xyz.pdf
- Determination of normal gravity (BGI document): bgi.omp.obs-mip.fr/content/download/723/9056/file/BGI_Normal_gravity_determination.pdf
- Définition des anomalies gravimétriques (in French): bgi.omp.obs-mip.fr/content/download/724/4972/file/FORMUL00.pdf
- Gravity definitions & anomaly computations (NGA document): bgi.omp.obs-mip.fr/content/download/725/4975/file/computations.pdf
- Description of the International Database for Absolute Gravity Measurements: bgi.omp.obs-mip.fr/content/download/727/4992/file/AGrav_Wziontek_etal2.pdf
  See also: (Wilmes et al. 2009).

Apart from the product descriptions a number of tutorials are offered in English and French language providing the fundamentals of gravity theory and satellite geodesy.
See: bgi.omp.obs-mip.fr/data-products/Documentation/tutorials.

4.5.3 ISG – International Service for the Geoid

ISG activities are on educational, research, and data distribution sides : principal purposes of ISG are the collection and distribution of geoid models, the collection and distribution of software for geoid computation, and the organisation of technical schools on geoid determinations. The tasks of the ISG are

- to collect geoid data on a worldwide scale (geoid repository)
- to collect and distribute software for geoid determination (software download)
- to conduct researches on procedure for geoid determination (projects)
- to organize Geoid schools
- to edit and distribute the Newton's Bulletin

The products of the International Service for the Geoid (ISG) are

- Grids of local and regional geoid estimates, collected worldwide (geoid repository).
- Geoid Software (local geoid estimation; spherical harmonics manipulation; global models handling, evaluation of different functionals of the gravity field). As this is specific software and not a data product no standards and conventions are identified.
- International schools on geoid determination and thematic schools. As this is not a data product no standards and conventions are identified.

More details about tasks and products can be found at the service web site www.isgeoid.polimi.it/index.html and in the following documents offered by the web site:

- Geoid model specifications:
  www.isgeoid.polimi.it/Geoid/ISG_format_20160121.pdf
- Software is provided via this web link:
  www.isgeoid.polimi.it/Software/software.html

4.5.4 ICGEM – International Center for Global Earth Models

The International Center for Global Earth Models collects and distributes historical and actual global gravity field models of the Earth and offers calculation service for derived quantities. In particular this includes: Collecting and archiving of all existing global gravity field models, maintaining an online archive for getting access to global gravity field models, providing web based visualization of the gravity field models, their differences and their time variation, offering a service for calculating different functionals of the gravity field models, and providing tutorials on spherical harmonics and the theory used by the calculation service.

The products of International Centre for Global Earth Models (ICGEM) are

- Static gravity field models as spherical harmonic series.
- Gravity field solutions for dedicated time periods (time variable model series) as spherical harmonic series.
  Monthly, weekly and daily solutions with or without applying non-isotropic filtering.
- Topographic gravity field models model . . . spherical harmonic series in ICGEM format (topography heights and gravitational potential).
- Calculation of gravity functionals on freely selectable grids or on user defined points. The following functionals are implemented so far: height anomaly, geoid height, gravity disturbance, gravity anomaly, Bouguer anomaly, gravity, gravitation, radial gravity gradient, equivalent water height.
- Visualization service for static and temporal gravity field model functionals, trends and amplitudes for temporal fields and spherical harmonics.
- Evaluation of gravity field models by degree variances and by GNSS-levelling comparisons.
- Additionally ICGEM offers also gravity field models of other celestial bodies (Moon and Mars) including the calculation and visualization service.

More details about tasks and products can be found at the service web site icgem.gfz-potsdam.de/home and in the following documents offered via the web site:

- The theory and formulas used by the calculation service of the ICGEM are described in the Scientific Technical Report STR09/02:
  icgem.gfz-potsdam.de/str-0902-revised.pdf
- Article about global models:
  icgem.gfz-potsdam.de/GlobalModelsEncyclopedia.pdf
- Description of the ICGEM format:
  icgem.gfz-potsdam.de/ICGEM-Format-2011.pdf
- Information on the topographic gravity field models:
  icgem.gfz-potsdam.de/Topomodels_description_ICGEM.pdf

4.5.5 COST-G – International Combination Service for Time-variable Gravity Fields

COST-G is the product centre of IGFS for standardization of gravity derived mass transport products in order to improve the quality, robustness and reliability of individual solutions and in order to enable hydrologists, glaciologists, oceanographers, geodesists and geophysicists to take full advantage of one well-defined, consolidated time variable gravity product. COST-G tasks are: (1) Developing the synergy between international teams working on gravity field modelling; (2) Improving and homogenizing the modelling adopted by the Analysis Centers (AC); (3) Providing combined reference solutions by the Combination Center (CC); (4) Assessing the reference solutions by a Validation Center (VC); (5) Organizing dissemination by a dedicated webmaster (WM). The combination service infrastructure will improve the actual standards and turn it into an operational mode that will enable the use of Gravity Recovery And Climate Experiment (GRACE) and Gravity Recovery And Climate Experiment – Follow On (GRACE-FO) mass redistribution data for monitoring hydrological events such as floods or droughts for instance. COST-G will provide consolidated time-variable global gravity models in terms of spherical harmonic coefficients and thereof derived grids by combining solutions from individual analysis centres as well as validation criteria which will be made available through dedicated web-interfaces.

The main products of COST-G are monthly global gravity field models derived from the combination of solutions from the COST-G analysis centres and partner analysis centres. In particular products at different processing levels are provided: Monthly global gravity field models in terms of spherical harmonic coefficients (Level-2 products). Post-processed Level-2 products in terms of spherical harmonic coefficients with various corrections applied (Level-2B products). User-friendly grids based on Level-2B products (Level-3 products) for various scientific applications as described at GFZ's Gravity Information Service (GravIS, gravis.gfz-potsdam.de/home).

Apart from these main products COST-G is also offering additional products helping to process the main products: Monthly means of background models that are generated by a weighted combination of the corresponding products of the individual analysis centres (applying the same weights as used for the generation of the combined gravity field models) Monthly means of combined atmosphere and ocean de-aliasing products.

The COST-G products are disseminated via ICGEM and GFZ's ISDC at icgem.gfz-potsdam.de/series/02_COST-G/ and ftp://isdcftp.gfz-potsdam.de/grace/GravIS/COST-G respectively. The COST-G Processing Standards and Release Notes are available at cost-g.org/download/COST_G_STANDARDS.pdf and cost-g.org/download/COST_G_RL01.pdf, respectively. Visualizations of the COST-G products are provided by GFZ's Gravity Information Service (GravIS, gravis.gfz-potsdam.de) and the COST-G Plotter (cost-g.org/).

4.5.6 IDEMS – International Digital Elevation Model Service

The website of the IAG International Digital Elevation Model Service (IDEMS) provides a focus for distribution of data and information about digital elevation models, spherical-harmonic models of Earth's global topography, lunar and planetary Digital Elevation Model (DEM), relevant software and related datasets. All information is provided via the service web site www.cse.dmu.ac.uk/EAPRS/iag/.

Currently, this site hosts different categories about products and information about DEMs, namely:

- Bathymetry and Ice Data,
- Earth Models,
- Geodesy relevant DEM and Bathymetric Terrain Model (BTM) Studies
- Global DEMs
- Planetary Terrain Data
- Regional DEMs
- Software and Apps
- Using DEMs and Esri Products.

The products of IDEMS are:

- Compilation, tutorial-style provision and maintenance of information on global gridded DEMs;
- Compilation of available national elevation data sets with information on data resolution, methods used for DEM generation and links to providers;
- Generation and dissemination of spherical-harmonic models of Earth's global topography and bathymetry;
- Compilation of geodesy-relevant DEM-studies;
- Extension of the focus from Earth to Moon and terrestrial planets through compilation of information on available planetary topography models.

The service does hardly provide data products via its web site, but mostly links to other institutional, project related or satellite mission web sites, where digital elevation models are made available. Standards and conventions for IDEMS products are not specified and no documentation about the most important digital elevation products is provided. Only a short tutorial "Getting started with IDEMS" an introduction to DEMs, and a bibliography is provided via the web site. The tutorial about the IDEMS in the present form is a mix of a general user manual and some kind of ArcGIS advertisement. From the information available at the web site it is not immediately obvious which models are freely accessible to the public.

4.5.7 IGETS – International Geodynamics and Earth Tide Service

The International Geodynamics and Earth Tide Service (IGETS) provides a service to monitor temporal variations of the Earth gravity field through long-term records from ground gravimeters, tiltmeters, strainmeters and other geodynamic sensors. IGETS is composed by two analysis centres hosted by University of French Polynesia in Tahiti and by University of Strasbourg and by a main data centre hosted GFZ Potsdam. Additionally, University of Strasbourg is hosting the central bureau and a secondary data centre. More details about IGETS can be found on the following web site: igets.u-strasbg.fr/index.php.

The main products of IGETS are the raw and processed data from worldwide superconducting gravimeters. In particular data at different processing levels are provided. These are :

- Raw gravity and local pressure records sampled at 1 or 2 seconds, in addition to the same records decimated at 1-minute samples (Level 1 products).
- Gravity and pressure data corrected for instrumental perturbations, ready for tidal analysis (Level 2 products).
- Gravity residuals after particular geophysical corrections (including solid Earth tides, polar motion, tidal and non-tidal loading effects) (Level 3 products).

Apart from these main products IGETS is also offering additional products helping to process the main products (via links to other web sites). These are :

- Superconducting gravimeter data for major Earthquakes (minute and second sampling);
- Atmospheric attraction computation service;
- mGlobe Matlab/Octave toolbox for computation of global hydrological, atmospheric and non-tidal ocean loading effects;
- Loading service (displacements, gravity, tilts).

Details about the main IGETS products can be found at the ISDC Web site of GFZ at isdc.gfz-potsdam.de/igets-data-base/documentation/. In particular there is available a report providing documentation and conventions for the IGETS products. See gfzpublic.gfz-potsdam.de/pubman/item/escidoc:1870888:7/component/escidoc:1948897/STR-1608_voigt.pdf.

4.5.8 IGFS Products Inventory of Standards

From the descriptions provided in the previous chapters the following product categories of the IGFS can be summarized. For these product categories certain standards and conventions need to be identified such that they are compatible (product identifier: product description):

BGI1 Land and marine gravity data and gravity data at reference stations
BGI2 Absolute gravity station data
BGI3 Grids of gravity anomalies
ISG1 Grids of regional geoid solutions
ICGEM1 Global gravity field model as spherical harmonic series (static, time variable)
ICGEM2 Gravity field functionals on a grid
IDEM1 Grids of digital elevation models
IGETS1 Superconducting gravimeter data

Products which are not mentioned above either shall not be regarded as a data product (e.g. geoid software, schools) or are not specified in sufficient detail in order to identify if standards and conventions play a role at all. So far metadata definitions have only been generated for geoid and gravity data either on grids or point-wise. Metadata for spherical harmonic series still need to be defined, but are overlapping to a large extent with metadata elements as defined for gravity and geoid products. The following list summarizes metadata, which are related to standards and conventions (metadata code and metadata description). The numbers are indicating the metadata field number, while letters indicate if a metadata entry is either specified for the geoid (**N**), for gravity observations (**G**) or both (**A**).

Metadata related to product standards and conventions:

A4.1.1 Gravitation constant of the Earth (GM)
A4.1.2 Equatorial radius of the Earth
A4.1.3 Flattening of the Earth
G4.1.4 Reference ellipsoid for normal gravity computation
A4.2.1 Permanent tide system
G4.2.2 Permanent tide system Earth orientation parameters
N4.3 Reference ellipsoid for geoid heights
G4.3 Earth orientation parameters specifications
N4.4 Standard density of the Earth value
G4.4.1 Solid Earth tides
G4.4.2 Solid Earth pole tide model
G4.4.3 Oceanic pole tide model
G4.4.4 Tidal ocean loading
G4.4.5 Non-tidal ocean loading model
G4.4.6 Non-tidal atmospheric loading model
G4.5.1 Horizontal and vertical coordinates
G4.5.2 Standard density of the Earth value
G4.5.3 Vertical gravity gradient
G4.5.4 Air pressure correction
A5.4 Data distribution: points or grid and grid specifications
N5.5.1 Geoid model type (gravimetric, hybrid, etc.)
N5.5.2 Fitting or integration methodology
G5.5 Gravity data type (absolute, type of anomaly, etc.)
N5.6 Geoid height data type (undulation or height anomaly)
G5.8 Time period and time reference

The following Table 4.7 provides a summary of the identified standards and conventions for the above mentioned IGFS products and specifically if they are addressed by the metadata descriptions (✓= metadata description available; N/A = not applicable for this product). Each line in the table represents one of the above mentioned metadata. In case additional metadata are needed for specific products they are indicated by additional lines in the table. So far the following additional metadata were identified: Degree = Maximum degree of spherical harmonic series applied to determine the product; Filter = Indication if a filter has been applied and what filter parameters were used.

4.5.9 Recommendations

The updated IGFS web-site acts as an umbrella for all its services and provides basic information about their tasks and products. The services of the IGFS shall ensure that all metadata required to make use of their products are delivered together with the products. In order to make product conversions to different representations or reference systems the required algorithms shall be described in the IGFS services documentation. For this purpose it is recommended to create a unique document per service (or even better for the IGFS), where these algorithms are described in detail. Some services of the IGFS could provide information about their products in a more concise way. Further remark on BGI and IDEMS: Many of the products collected by these services are not publicly available. Although they appear as IAG Services, this data is not available for research within the IAG. From the analysis of the services and their products some recommendations can be drawn.

Recommendation 5.1 : For all IGFS products (i.e. from the affiliated services and centres) metadata as specified by the IGFS-CB shall be provided. If needed, further metadata categories in addition to geoid and gravity shall be developed by the IGFS-CB.

Table 4.7: Summary of the identified standards and conventions for IGFS products.

	BGI1	BGI2	BGI3	ISG1	ICGEM1	ICGEM2	IGETS1
A4.1.1	✓	N/A	✓	✓	✓	✓	✓
A4.1.2	✓	N/A	✓	✓	✓	✓	✓
A4.1.3	✓	N/A	✓	✓	✓	✓	✓
G4.1.4	✓	N/A	✓	N/A	N/A	✓	✓
A4.2.1	✓	✓	✓	✓	✓	✓	✓
G4.2.2	✓	✓	✓	N/A	N/A	N/A	✓
N4.3	N/A	N/A	N/A	✓	N/A	✓	N/A
G4.3	✓	✓	✓	N/A	N/A	N/A	✓
N4.4	N/A	N/A	N/A	✓	N/A	N/A	N/A
G4.4.1	✓	✓	✓	N/A	N/A	N/A	✓
G4.4.2	✓	✓	✓	N/A	N/A	N/A	✓
G4.4.3	✓	✓	✓	N/A	N/A	N/A	✓
G4.4.4	✓	✓	✓	N/A	N/A	N/A	✓
G4.4.5	✓	✓	✓	N/A	N/A	N/A	✓
G4.4.6	✓	✓	✓	N/A	N/A	N/A	✓
G4.5.1	✓	✓	✓	N/A	N/A	✓	✓
G4.5.2	✓	N/A	✓	N/A	N/A	N/A	✓
G4.5.3	✓	N/A	✓	N/A	N/A	N/A	✓
G4.5.4	✓	✓	✓	N/A	N/A	N/A	✓
A5.4	✓	✓	✓	✓	N/A	✓	✓
N5.5.1	N/A	N/A	N/A	✓	N/A	✓	N/A
N5.5.2	N/A	N/A	N/A	✓	N/A	✓	N/A
G5.5	✓	✓	✓	N/A	N/A	✓	✓
N5.6	N/A	N/A	N/A	✓	N/A	✓	N/A
G5.8	✓	✓	✓	N/A	✓	✓	✓
Degree	N/A	N/A	N/A	N/A	N/A	✓	N/A
Filter	N/A	N/A	N/A	N/A	N/A	✓	N/A

Recommendation 5.2 : BGI shall collect and distribute grids of altimetric gravity anomalies. So far these data are not yet offered by the IGFS.

Recommendation 5.3 : BGI and IGETS partially are providing similar products, i.e. observations from ground gravimeters. It is recommended that both services implement joint standards for these products in order to ensure compatibility.

Recommendation 5.4 : The ISG Software has some overlap with the on-line tools available at the ICGEM. It is strongly recommended to make sure that both Software systems are compatible, i.e., that the same standards and conventions are used.

Recommendation 5.5 : COST-G products shall be disseminated via the ICGEM. It is recommended not to establish a separate service for provision of combined time variable gravity field series. Same standards as used by ICGEM (e.g. format) shall be applied. What concerns mass transport grids, it shall be made sure that these are as well compatible to the ICGEM calculation service. In addition the relationship to the GFZ driven GravIS system shall be defined and ideally both shall be combined.

Recommendation 5.6 : The IDEMS in the present form cannot be regarded as a product repository as it hardly provides access to real digital elevation data grids. At various places on the IDEMS web pages links to ArcGIS are set. In order to make full use of the web site an ArcGIS software license seems to be needed. So IDEMS shall not be regarded as an open access scientific service, but a mix of service and public relation for ESRI who is maintaining the IDEMS web site. It is strongly recommended to separate the web site content to a product service part, which should point towards accessible DEM's (the real IDEMS) and another section which might be more related to ArcGIS applications.

Recommendation 5.7 : All products to be delivered under the umbrella of IGFS shall be publicly available for research applications. Otherwise these products shall not be advertised anymore as IGFS supported products.

4.6 Height systems and their realisations

In the first version of this inventory, published in 2016 (Angermann et al. 2016), the section "Height Systems and their realisations" concentrated on the discrepancies of the local height systems and their combination with geometric (ellipsoidal) heights and (quasi-)geoid models. Special care was given to the inventory of corrections or reductions applied to the different vertical coordinates to remove or retain geophysical effects influencing the vertical positioning. In this updated version of the inventory, we add a description of the standards that are being discussed (as of December 2019) for the implementation of the International Height Reference System (IHRS) and its realisation, the International Height Reference Frame (IHRF), as stated by the IAG Resolution No. 1, 2015 released in the IUGG2015 General Assembly (Drewes et al. 2016).

4.6.1 Overview

Currently, a formal *GGOS height systems product* or an *IAG Height Systems Service* does not exist. However, the availability of geodetic space techniques, especially GNSS and dedicated-gravity field missions (i.e., CHAMP, GRACE, GOCE), motivates the combination of current geodetic products to determine gravity field-related heights. This combination is normally performed according to the relation $h-H-N=0$. The ellipsoidal heights (h) are derived from GNSS positioning while the geoid or quasi-geoid models (N) are computed combining satellite and terrestrial (aerial, marine) gravity data. The orthometric or normal heights (H) are usually obtained from spirit levelling (+ gravity reductions) referring to local vertical datums.

The determination of ellipsoidal heights is expected to conform to the IERS and IGS standards, since these heights depend on the geocentric Cartesian coordinates and on the size, orientation, and position of the reference ellipsoid used for their transformation into ellipsoidal coordinates. For the computation of the (quasi-)geoid, a compilation of standards (like the IERS conventions) is not available. The processing of CHAMP, GRACE and GOCE data is well-documented in the specific guidelines (Dahle et al. 2013; Gruber et al. 2010; Lühr et al. 2002). However, the computation of the long-wavelength constituents of the (quasi-)geoid (degree $n \leq 200 \ldots 250$ in a spherical harmonic expansion) produces different results depending on the combination of satellite-based gravity data and the processing strategy used for the estimation of the spherical harmonic coefficients. The medium to short-wavelength components ($n > 250$) of the (quasi-)geoid are usually estimated by combining surface (terrestrial, airborne, marine) gravity data and the gravitational effects of the topography derived from digital terrain models. In this case, information about the mass density (either by digital density models or density hypotheses) is also necessary.

For the treatment of the surface gravity, the standards published with the International Gravity Standardization Net 1971 (IGSN71) (Morelli et al. 1974) and the International Absolute Gravity Basestation Network (IAGBN) (Boedecker 1988) are available. Nevertheless, there are still large data bases referring to the old gravity reference called Potsdam system (Borrass 1911). Gravity surveys with geophysical purposes (e.g., oil exploration) are in general not freely available and the standards applied to their processing are not clear.

Historically, the determination of the physical heights initially followed two basic conventions: (1) the geoid coincides with the mean sea level and (2) the corresponding vertical coordinate must be the orthometric height. The realisation of these conditions was carried out by estimating the local mean sea level at selected tide gauges and by means of geodetic levelling in combination with gravity reductions. It should be stressed that orthometric heights depend on the mass density distribution in the Earth's interior which is not known at a sufficient degree. Any hypothesis about the density distribution creates a different realisation of the orthometric height system, but also of the geoid as a level surface running in the Earth's interior over the continents. Alternatively, and since about the middle of the 20th century, some height systems are based on normal heights and the quasi-geoid as the reference surface. The geoid and the quasi-geoid are practically identical in marine areas, and the realisation of the quasi-geoid can also be set equivalent to the local mean sea level at the reference tide gauges. In general, the existing physical heights not only refer to local (unconnected) levels but are also static (without considering variations in time) and contain large uncertainties caused primary by systematic errors in levelling, omission or different approximations in the gravity reductions, and non-modelled effects in the height determination (more details in Table 4.8).

Considering these characteristics, it is clear that the state-of-the-art allows the combination of ellipsoidal and physical heights with (quasi-)geoid models with an accuracy varying from some cm up to 2 m. This may satisfy some practical applications, but measuring, understanding and modelling global change effects with magnitudes at cm- or mm-level is not possible. The solution of these deficiencies requires the establishment of a gravity field-related global vertical reference system, capable of supporting the standardisation (unification) of the existing height systems and the precise combination of physical and geometric heights globally. The implementation of such a vertical reference system is a main objective of GGOS (see GGOS Focus Area *Unified Height System* in GGOS 2020 Action Plans 2011–2015, unpublished) and the success of this initiative has to be necessarily supported by a clear statement of standards and conventions.

Table 4.8: Characteristics and present status of the existing physical height systems.

Characteristics	Present status
Reference level and vertical datum	
– **Definition**: the geoid according to Gauss (1876) and Listing (1873). – **Basic convention**: the geoid coincides with the undisturbed mean sea level. – **Realisation**: mean sea level averaged over a certain period of time at an arbitrarily selected tide gauge. – **Remark**: The interpretation of this convention has changed over the years depending on the type and quality of geodetic observations and analysis strategies available for modelling both the mean sea surface and the geoid, e.g., (Ekman 1995; Heck 2004; Heck and Rummel 1990; Mather 1978; Sánchez 2012).	– There are as many vertical datums as reference tide gauges (at present more than 100 worldwide) and the reference levels relate to different determination epochs. – Height systems based on the quasi-geoid realise the reference level and the vertical datum in the same manner because geoid and quasi-geoid are practically identical in ocean areas and at the coast lines (where the tide gauges are established).
Vertical coordinates	
– **Definition**: orthometric heights (as *tacit* consequence of introducing the geoid as the reference surface). – **Realisation**: levelling with gravity reductions (in same cases using normal gravity instead of observed surface gravity). – **No convention** about the gravity reduction (sometimes no reduction). – **Remark**: Normal heights and quasi-geoid are preferred in some countries/regions.	– Vertical coordinates realise different orthometric height types depending on the applied orthometric hypothesis. – There is no unique relation between reference surface and vertical coordinates if the geoid is not computed using the same orthometric hypothesis as applied for the orthometric heights. – The determination of normal heights does not depend on any orthometric hypothesis, but only on the parameters of the reference ellipsoid. The same holds for the quasi-geoid.
Reference frames	
– The **vertical control** over continental areas has been extended by means of spirit levelling along vertical networks. – **Drawbacks**: levelling is very time-consuming and the systematic errors significantly grow with the distance from the reference tide gauge.	– Most of the vertical networks have been measured piece-wise over very long time periods and the vertical coordinates refer to different epochs. – The estimation of vertical displacements at levelling points by spirit levelling is very difficult (expensive) and in most cases they are neglected. – The accuracy of the heights is limited regionally by the error propagation of spirit levelling to dm-level in remote areas and globally by the datum realisation to m-level.

4.6.2 Summary of standards

As a first attempt, the inventory of the standards used in height systems concentrates on the effects removed or retained in the different coordinates associated with vertical positioning; i.e., those corrections (or reductions) applied to the instantaneous station positions to generate *regularised* or *quasi-static* coordinates. The coordinates considered are: geometry on land (station positions derived from GNSS positioning), terrestrial gravity (relative and absolute gravity values measured on or near the Earth's surface), geopotential numbers (derived from levelling in combination with gravity reductions), and (quasi-)geoid models. To identify which standards have to be taken into account in this inventory, Table 4.9 summarises the magnitude of the main effects currently considered.

Apart from the effects caused by secular changes (represented by the so-called *station velocities*), the largest magnitudes are related to the treatment of the permanent tide (see Section 3.2). In the case of the geometrical coordinates (i.e., ITRS/ITRF), the realisation of the tide-free system is based on the elastic response of the Earth to the semidiurnal components of the tidal potential (cf. nominal Love numbers (Petit and Luzum 2010, Chapters 6 and 7)). This approximation is called the *conventional tide-free system*. In the terrestrial gravity and spirit levelling processing, the tide-free system assumes the Earth in a hydrostatic equilibrium (cf. secular or fluid limit Love numbers (Munk and MacDonald 1960)). This approximation is called the *tide-free system*. These two different approximations cause discrepancies up to 0.16 m in the *tide-free vertical coordinates*. The computation of the (quasi-)geoid is done in the tide-free or zero-tide system. However, some models apply the elastic response approximation and others apply the hydrostatic equilibrium condition. In this way:

- the geometric coordinates are given in the conventional tide-free system;
- the terrestrial gravity data are given in general in the zero-tide system (following the IAG Resolution No. 16, 1983), but some values determined before 1983 refer to the tide-free system;
- the geopotential numbers are given in the tide-free, zero-tide or mean-tide system. This depends on the application of the so-called *astronomical reduction to levelling*. This reduction produces coordinates in the tide-free system. If the indirect effect of the permanent tide is restored, they are given in the zero-tide system. If the astronomical reduction is not taken into account, the geopotential numbers are assumed to be in the mean-tide system;
- the global gravity models and the derived (quasi-)geoid models are published in the conventional tide-free or zero-tide system. The mean-tide system is also used especially for oceanographic applications.

The tide-generating potential is modelled according to :

- for the geometric coordinates (following IERS Conventions): Cartwright and Edden (1973) and Cartwright and Tayler (1971). Transformation parameters to the models of Doodson (1921) and Hartmann and Wenzel (1995) are also provided;
- for the CHAMP, GRACE, and GOCE data: the same as the IERS Conventions;
- for the terrestrial gravity: beside the Cartwright model (Cartwright and Edden 1973; Cartwright and Tayler 1971), the Longman (1959) formulation was also widely applied before IGSN71. In recent years, the model of Hartmann and Wenzel (1995) is also used.

The changes induced by the solid Earth tides (estimated by means of Love numbers) in the IERS Conventions are computed following the models of Wahr (1981) and Mathews et al. (1995) in combination with the model Preliminary Reference Earth Model (PREM) (Dziewonski and Anderson 1981). Further corrections for the anelasticity of the mantle and resonance effects caused by oceanic currents and tides, and the Chandler wobble, the retrograde Free Core Nutation (FCN) and the prograde Free Inner Core Nutation (FICN) are also included. The estimation of the pole tide and ocean pole tide effects is based on (Wahr 1985), but using the so-called *fluid Love numbers* (Munk and MacDonald 1960), i.e., the deformation for an Earth in hydrostatic equilibrium. Here it should be mentioned again that the direct deformation of the Earth's surface caused by the tide-generating potential is estimated applying (frequency-dependent) Love numbers for an elastic Earth. The ocean pole tide loading is computed using the model of equilibrium of Desai (2002). The pole tide and ocean pole tide loading effects in GRACE and GOCE and in terrestrial gravity data of high-precision (absolute and superconducting gravimetry) are computed as in the IERS Conventions.

The ocean loading effects in the geometric coordinates are modelled according to Farrell (1972) and using the *conventional computation routine* of Scherneck (1991) described in the IERS Conventions. The ocean tide models preferred by the IERS are TPXO 7.2 (Egbert et al. 1994) and FES2004 (Letellier and Lyard 2005), while in the analysis of GRACE and GOCE data the model FES2004 is used.

Non-tidal effects (from ocean, atmosphere and hydrology) are not removed from the geometrical coordinates; i.e., these effects are included in the station positions. In the IERS Conventions, the atmospheric tidal effects caused by the solar diurnal and semidiurnal components are modelled according to (Ray and Ponte 2003), while in the GRACE data processing the model of Biancale and Bode (2006) is used. GOCE data processing does not reduce this effect directly; it is modelled together with non-tidal effects.

Table 4.9: Summary of geophysical effects and their magnitudes.

Effect	**Geometry on land**	**Terrestrial gravity**	**Geopotential numbers**	**Geoid**
Solid Earth permanent tide	elastic response of the Earth -0.12 m at pole, $+0.06$ m at equator, or hydrostatic equilibrium -0.28 m at pole, $+0.14$ m at equator	hydrostatic equilibrium at pole: $+0.61\,\mu\mathrm{m\,s^{-2}}$ at equator: $-0.30\,\mu\mathrm{m\,s^{-2}}$	equipotential surfaces move as the geoid, but simultaneously	anelastic response of the Earth -0.19 m at pole, $+0.10$ m at equator
Periodic components of the Solid Earth tide (modelled as elastic response of the Earth)	at pole: -0.18 m (Moon), -0.08 m (Sun), at equator: $+0.36$ m (Moon), $+0.16$ m (Sun)	Moon: -1.1 to $+0.5\ \frac{\mu\mathrm{m}}{\mathrm{s}^2}$, Sun: -0.5 to $+0.3\ \frac{\mu\mathrm{m}}{\mathrm{s}^2}$	Moon: ± 0.056 mm per km of levelling, Sun: ± 0.026 mm per km of levelling	as undisturbed sea level -0.26 m at pole, $+0.52$ cm at equator
Solid Earth pole tide (modelled as hydrostatic equilibrium)	± 0.0270 m (vert), ± 0.0070 m (hz)	$< +0.082\,\mu\mathrm{m\,s^{-2}}$ (at latitude 45°)	± 3 cm in 430 days	± 0.0270 m
Oceanic pole tide (modelled as hydrostatic equilibrium)	± 0.0018 m (vert), ± 0.0005 m (hz)	unknown	negligible	± 0.0018 m
LOD variations (modelled as hydrostatic equilibrium)	up to 1 m	0.0007 to 0.007 $\frac{\mu\mathrm{m}}{\mathrm{s}^2}$	negligible	negligible
Tidal ocean loading	± 0.10 m	$\pm(0.01$ to $0.02)\ \frac{\mu\mathrm{m}}{\mathrm{s}^2}$	negligible	unknown
Non-tidal ocean loading	unknown	unknown	unknown	10 mm in 100 to 1000 km
Tidal atmospheric loading	± 0.0015 m	$<\ 0.003\,\mu\mathrm{m\,s^{-2}}$	negligible	unknown
Non-tidal atmospheric loading	unknown	-0.003 to -0.004 $\mu\mathrm{m\,s^{-2}}$/hPa	unknown	15 mm in 20 to 2000 km
Tidal hydrologic loading (groundwater)	± 0.050 m	unknown	negligible	unknown
Non-tidal hydrologic loading (groundwater, snow, ice)	± 0.050 m	0.05 to 0.1 $\mu\mathrm{m\,s^{-2}}$	unknown	10 to 12 mm in 10 to 8000 km
Secular changes (like tectonics, GIA, subsidence, etc.)	up to 0.1 m/yr	unknown	up to 0.1 m/yr	unknown

The non-tidal effects in the case of GRACE and GOCE are understood as short-term mass variations of the atmosphere-ocean system. The corresponding effects are reduced from the spherical harmonic coefficients directly to get a quasi-stationary representation of the Earth's gravity field. The estimation of this reduction is based on the Ocean Model for Circulation and Tides (OMCT) (Thomas 2002) combined with the numerical weather models produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). Hydrological effects are assumed to be contained in the epoch-gravity models computed from GRACE.

In the computation of terrestrial gravity anomalies, the atmospheric effects are modelled by means of a standard atmosphere, i.e., a spherical model considering radial density changes only. In some cases, this approximation is refined by taking into account the perturbations caused by the terrain irregularities in the atmosphere-Earth surface coupling. The estimation of this reduction is based on an inverse Bouguer plate with the mean density of the atmosphere.

Regarding the level differences measured by geodetic levelling, the only applied reduction is the astronomical correction; the other effects (like pole tide, ocean pole tide, non-tidal loading, etc.) are considered insignificant (Heck 1984).

4.6.3 Discussion and deficiencies

According to the summary presented in the previous sections, the largest discrepancies of the existing height systems and their combination with geometrical heights and (quasi-)geoid models are caused by:

- different reference levels (i.e., zero-height surfaces) in the local height systems;
- datum inconsistencies associated with the individual vertical coordinates, e.g., no coincidence between the zero-height level of the vertical networks and the level of the (quasi-)geoid models;
- omission or different approximations in the computation of gravity reductions in the levelling data; i.e., different types of physical heights (orthometric, normal, normal-orthometric, etc.);
- vertical coordinates associated with different reference epochs (in general, dH/dt is unknown and therefore omitted);
- systematic effects and distortions, e.g., long-wavelength (quasi-)geoid errors, poorly modelled radial effects in GNSS positioning, over-constrained levelling network adjustments, systematic errors in levelling, etc.;
- assumptions and theoretical approximations taken into account for the data processing; e.g., hypotheses in geoid and orthometric height computation, atmospheric delay in GNSS, neglecting ocean dynamic topography at tide gauges, etc.;
- dissimilar approaches to reduce the same effect in the different height types, in particular, the treatment of the luni-solar permanent tide;
- systematic and random errors in the different height types h, H, and N.

To overcome these deficiencies, it is necessary, among other tasks,

- to unify (standardise) the existing height systems; i.e., to refer all physical heights to one and the same reference level (defined and realised globally);
- to introduce geopotential numbers as the primary vertical coordinate in order to avoid inconsistencies caused by different gravity reductions in the height determination;
- to guarantee that geometrical and physical heights represent the same Earth's surface geometry; i.e., the so-called regularised station positions should include consistent reductions, especially the treatment of the permanent tide. In the same way, the secular changes should be included in both representations: geometrical (dh/dt) and physical (dH/dt) heights;
- to adopt a conventional global gravity model to be used as the long-wavelength component in the estimation of (quasi-)geoid models of high resolution.

Table 4.10 shows some examples about the requirements and present limitations concerning the combination of physical and geometric heights.

4.6.4 The IAG resolution for the definition and realisation of an *International Height Reference System (IHRS)*

A first concrete step oriented to the establishment of a worldwide unified (standardised) vertical reference system is the release of an IAG resolution for the *definition and realisation of an International Height Reference System (IHRS)*. This resolution outlines five basic conventions for the definition of the IHRS. The definition is given in terms of potential parameters: the vertical coordinates are geopotential numbers ($-\Delta W_P = C_P = W_0 - W_P$) referring to an equipotential surface of the Earth's gravity field realised by the IAG conventional value W_0 = 62 636 853.4 m^{2}s^{-2}. The spatial reference of the position P for the potential $W_P = W(\vec{X})$ is given by coordinates $\vec{X}$ of the ITRF. The units of length and time are the meter (m) and the second (s) as expressed by the International System of Units (SI). This resolution also states that parameters, observations, and data should be related to the mean tidal system/mean crust. This is in contradiction with the IAG resolution No. 16 (1983); however, the mean tidal system is necessary to support oceanographic applications, especially in coastal areas. More details about the foundations of this IAG resolution can be found in (Ihde et al. 2017) and (Sánchez et al. 2016).

4.6.5 Towards an standardisation for the IHRS realisation

The convention $W_P = W(\vec{X})$, with $\vec{X} = [X,Y,Z]_{\mathrm{ITRF}}$ makes evident that the IHRS is based on the combination of a geometric component given by $\vec{X}$ and a physical component given by the determination of W at $\vec{X}$. $\vec{X}$ is to be determined in the ITRS/ITRF and consequently, it follows the IERS standards and conventions (see details in Section 4.2). The potential values W may be in general determined from geopotential numbers C_P or by solving the geodetic boundary value problem (GBVP). Geopotential numbers C_P are known from levelling with gravity reductions and the potential values W would be given by $W_P = W_0 - C_P$. However, as they refer to local vertical datums (different reference levels), this approach requires the vertical datum unification of the levelling-based height systems into the IHRS and its reliability is limited by the drawbacks of the existing height systems (see Table 4.8). Therefore, this approach is useful for the transformation of the existing height systems to the IHRS, but it is unsuitable for the precise realisation of the IHRS (Sánchez and Sideris 2017).

The determination of absolute potential values W_P from observational data is only possible after introducing adequate

Table 4.10: Requirements and present limitations concerning the combination of physical and geometric heights (taken from (Sánchez 2012)).

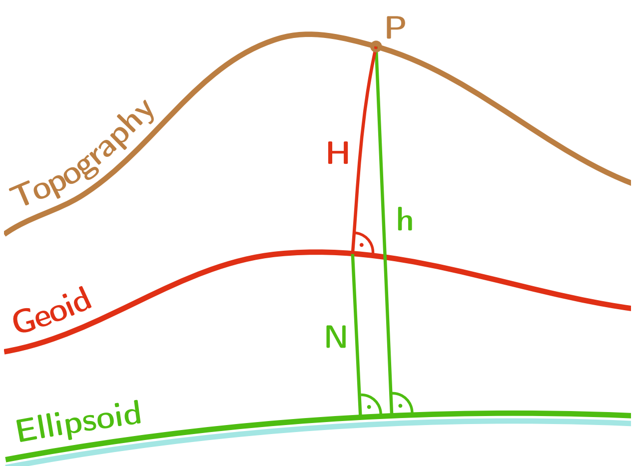
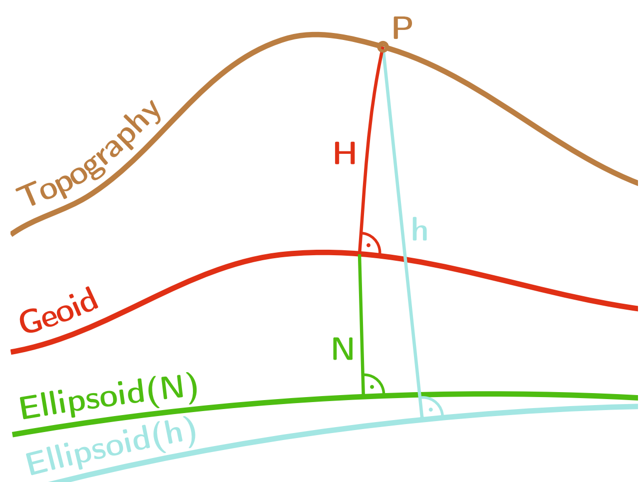
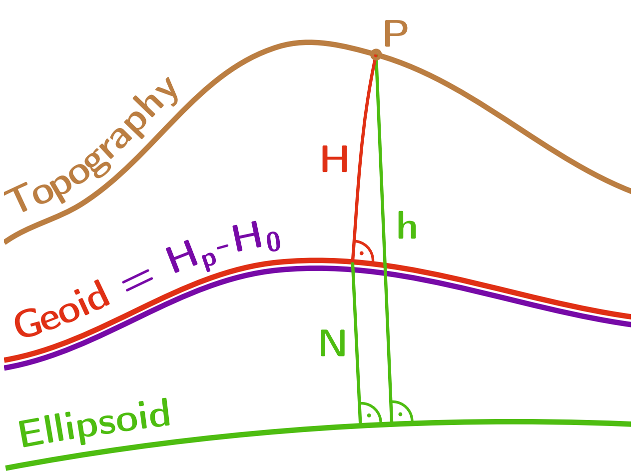
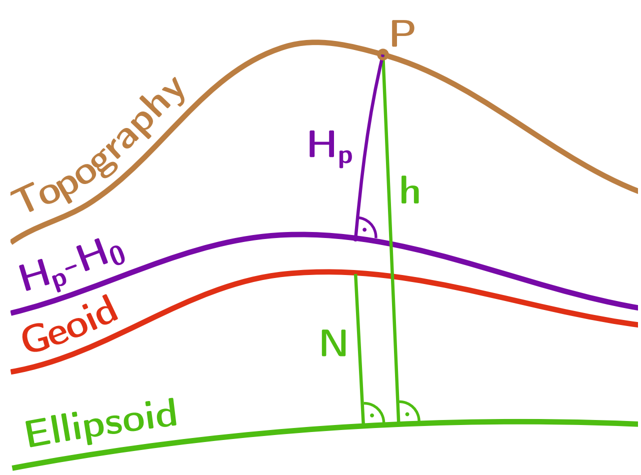
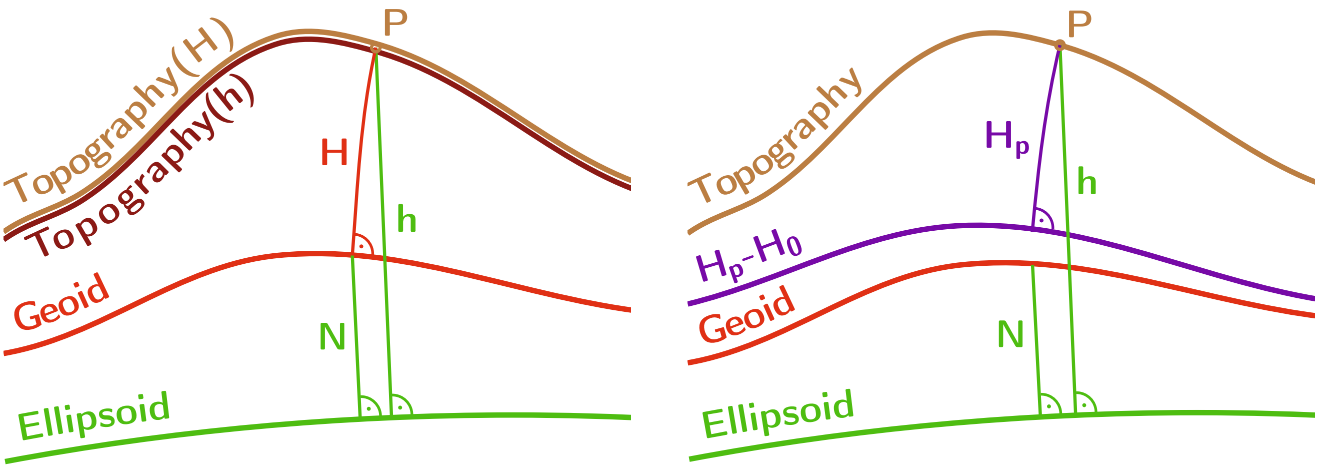
<table>
<tr><th>Requirement</th><th>Present status</th></tr>
<tr><td>Ellipsoidal heights h and (quasi-)geoid heights N must be given with respect to the same ellipsoid; i.e., the same ellipsoidal parameters have to be used
• for the transformation of geocentric Cartesian coordinates into ellipsoidal coordinates,
• as reference field for the solution of the geodetic boundary value problem,
• for scaling global gravity models, etc.</td><td>• Different ellipsoidal parameters (a, GM) are applied in geometry and gravity.
• h and N given in different tide systems; e.g,
– the mean-tide system in oceanography, satellite altimetry, levelling,
– the conventional tide-free system in ITRF positions, GRS80, some (quasi-)geoid models,
– the zero-tide system in some (quasi-)geoid models, terrestrial gravity data.</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Physical heights H and (quasi-)geoid undulations N must reflect the same reference surface; i.e., the height reference surface H_0 obtained by subtracting the physical height H from the ellipsoidal height h shall be consistent with the (quasi-)geoid derived from gravity (solution of the boundary value problem).</td><td>• Orthometric heights H and geoid models N obtained from the solution of the boundary value problem are based on different hypotheses.
• H and N refer to different tide systems.
• Systematic errors over long distances in levelling reduce the reliability of H_0.</td></tr>
<tr><td>
</td><td>
</td></tr>
</table>

Table 4.10 continued

Requirement	Present status
Physical heights H and ellipsoidal heights h must represent the same Earth's surface	• H and h refer to different epochs and, in the most cases, dH/dt is unknown. • Different reductions (for Earth-, ocean-, atmospheric tides, ocean and atmospheric loading, post-glacial rebound, etc.) are applied.



constraints. The main constraint is that the gravitational potential V must vanish at infinity; i.e., $V_\infty = 0$. Consequently, this constraint is the primary convention for the realisation of the physical component of the IHRS. In this context, the potential values W_P may be obtained using a global gravity model of high degree (GGM-HD) or by estimating the anomalous potential T_P after solving the GBVP. The potential values are given by $W_P = U_P + T_P$, where U is the potential of an appropriately selected reference ellipsoid.

The availability of GGM-HD, like the EGM2008 model (Pavlis et al. 2013, 2012) or the EIGEN-C series (e.g., Förste et al. 2015), makes it possible to carry out a direct computation of W_P by introducing the ITRF coordinates $\vec{X}$ of any point into the spherical harmonic expansion equation representing a GGM-HD. However, in areas with few terrestrial gravity data, the higher degrees of the GGM-HD do not contain the full signal of the Earth's gravity field and the so-called omission error increases strongly. According to Rummel et al. (n.d.), the expected accuracy after applying one of these models is $\pm 40\,\mathrm{cm^2s^{-2}}$ to $\pm 60\,\mathrm{cm^2s^{-2}}$ (equivalent to ± 4 cm to ± 6 cm) in well surveyed regions, and about $\pm 200\,\mathrm{cm^2s^{-2}}$ to $\pm 400\,\mathrm{cm^2s^{-2}}$ (± 20 cm to ± 40 cm) with extreme cases of $\pm 10\,\mathrm{m^2s^{-2}}$ (± 1 m) in sparsely surveyed regions. In addition, different GGM-HD deliver different potential values for the same position $\vec{X}$. This is probably a combined effect of including different gravity data of high-resolution (terrestrial, airborne and marine gravity data) and applying different standards, models and procedures in the estimation of the harmonic coefficients. As the realisation of the IHRS demands the best possible accuracy of the potential values (target is the sub-centimetre level $\approx \pm 10\,\mathrm{cm^2s^{-2}}$), the direct application of GGM-HD for the IHRS realisation is still considered to be inappropriate.

Regarding the solution of the GBVP, there is a long list of different approaches depending on the observables available for the formulation of the GVBP (e.g., Heck and Seitz 1993): fixed GBVP (boundary surface known, 3D position of the observables available), scalar-free GBVP (boundary surface unknown, horizontal position of the observables available), or a vector-free GBVP (boundary surface unknown, position of the observables unavailable). As the existing gravity data banks mainly contain gravity anomalies with latitude and longitude values, the scalar-free GBVP is the most used formulation presently. Its solution is faced applying different methodologies, for instance, the Stokes integral or the Molodensky series with unmodified or modified kernel functions, least-squares collocation, radial basis functions, spectral modifications, etc. A common strategy in these different methodologies is a remove-compute-restore procedure (Schwarz et al. 1990; Tscherning 1986). It allows the combination of the long-wavelength component provided by a satellite-only GGM with gravity observables of high-resolution (terrestrial, airborne and marine gravity data, deflections of the vertical, terrain gravity effects, etc.).

A rigorous standardisation of the method to solve the GBVP seems to be not suitable because (1) it exists different data availability and different data quality around the world (e.g. terrestrial gravity data, terrain models, GPS/levelling, etc.), and (2) regions with different characteristics require particular approaches (e.g. modification of kernel functions and size of integration caps depending on the terrestrial gravity data availability, or geophysical reductions like glacial isostatic adjustment effects, which are very much larger in polar regions than in equatorial zones). One possibility to overcome this issue would be a centralised computation of the potential values W_P in a similar way as the IERS combination centres determine the ITRF. However, this option is still unviable due to the restricted accessibility to terrestrial gravity data. To exploit at maximum the existing data to get as accurate as possible potential values, national/regional experts in the gravity field (or geoid) modelling should be involved in the determination of the IHRS/IHRF coordinates. They have access not only to terrestrial gravity data but also to terrain models of high-resolution, GNSS/levelling data, etc. The idea is that they utilise all the data they have available to determine the potential values using the computation approaches they have implemented for their regions. However, to minimise discrepancies and to obtain as similar and compatible results as possible with the different methods, a basic set of standards should be set up.

To advance in this purpose, during the Joint Scientific Assembly of the International Association of Geodesy (IAG) and the International Association of Seismology and Physics of the Earth's Interior (IASPEI) (Kobe, Japan, Aug 2017), it was agreed to initiate an empirical experiment (Sánchez 2019) towards:

- the computation of IHRF coordinates, geoid heights and height anomalies using exactly the same input data and the own methodologies (software) of colleagues involved in the gravity field modelling, and
- the comparison of the results, to highlight the differences caused by disparities in the computation methodologies and to identify a set of standards that allow to get as similar and compatible results as possible.

The input data for this experiment were provided by the US National Geodetic Survey (NGS) and contain terrestrial gravity data (59,303 points), airborne gravity data (41 lines in E-W direction and 7 lines in N-S direction), GNSS/levelling data (510 points) and a digital terrain model for an area of about 500 km x 800 km in Colorado, USA. The experiment is conducted under the cooperation of

- GGOS-JWG: Strategy for the Realisation of the IHRS (chair: L. Sánchez, Germany)
- IAG JWG 2.2.2: The 1 cm geoid experiment (chair: Y. M. Wang, USA)
- IAG SC 2.2: Methodology for geoid and physical height systems (chair: J. Ågren, Sweden)
- ICCT JSG 0.15: Regional geoid/quasi-geoid modelling – Theoretical framework for the sub-centimetre accuracy (chair: J. Huang, Canada)

The Colorado data were distributed in Feb. 2018, together with a document summarizing a minimum set of basic requirements (standards) for the computations (see section 4.6.6). Ten different groups delivered solutions and the results were discussed during the Gravity, Geoid and Height Systems (GGHS2018) Symposium (Copenhagen, Denmark, Sep 2018). Main conclusions are (Sánchez et al. 2018b; Wang et al. 2018):

- Two solutions were declared as outliers. They present large discrepancies (at the 1.5 m level) in (quasi-)geoid heights as well in the potential numbers with respect to the other solutions.
- In the geoid comparison, six solutions agree within 3 cm to 10 cm in terms of standard deviation with respect to the mean value.
- In the quasi-geoid comparison, the same six solutions agree within 1 cm to 4 cm in terms of standard deviation with respect to the mean value.
- In the comparison of the potential values, four solutions agree within 1 cm to 2 cm in terms of standard deviation with respect to the mean value.
- The discrepancies present a high correlation with the topography.

Possible sources of discrepancy are:

- Different handling of terrain corrections/reductions.
- Inconsistent use of the zero-degree term.
- Precision degradation due to the conversion of height anomalies to geoid heights and vice versa.
- Uncertainties in the processing of the airborne gravity data.

To refine the results, a second computation for the Colorado experiment was completed in Apr 2019. In total, 14 solutions were delivered. At present, the comparison of geoid heights, height anomalies and potential values is going on.

4.6.6 Preliminary standards for the IHRS realisation

This section summarises the basic agreements outlined for the computation of station potential values as IHRS coordinates, geoid undulations and height anomalies within the Colorado experiment.
They have been prepared by L. Sánchez (Deutsches Geodätisches Forschungsinstitut, Technical University Munich, Germany), J. Ågren (Lantmäteriet, Swedish mapping, cadastral and land registration authority, Sweden), J. Huang (Natural Resources Canada, Canada), Y. M. Wang (NOAA's National Geodetic Survey, USA), and R. Forsberg (National Space Institute, Denmark), see (Sánchez et al. 2018a).

Basics

- The determination of station potential values W_P as IHRS coordinates is straightforward if the disturbing potential T_P is known: $W_P = U_P + T_P$.
- The potential values realising the IHRS coordinates must be determined at the reference stations; i.e., at the Earth's surface and not at the geoid.
- According to the IHRS definition, the station coordinates have to be given in the mean-tide system. To be consistent with the GBVP definition, it is recommended to perform the computations in the zero-tide system and afterwards, to transfer the coordinates to the mean-tide system at the very end, using simplified formulas. This keeps the computations consistent with the gravity/geoid work in zero-tide without introducing many transformations and corrections.
- For these first experiments, we assume the Earth's gravity field to be stationary; i.e., time changes are disregarded so far.

Standards

General constants (numerical values needed for the solution of several equations):

- Constant of gravitation (G)
  6.67428×10^{-11} m^{3}kg^{-1}s^{-2}
- Geocentric gravitational constant (GM)
  $3.986004415 \times 10^{14}$ m^{3}s^{-2} (including the Mass of the Earth's Atmosphere)
- Nominal mean angular velocity of the Earth (ω)
  7.292115×10^{-5} rad s^{-1}
- Conventional reference potential value (W_0)
  $62\,636\,853.4$ m^{2}s^{-2}
- Average density of topographic masses (ρ)
  2670 kg m^{-3}. This topographic density shall be assumed when computing the geoid height.

Reference ellipsoid (to be used for the computation of gravity anomalies, disturbing potential, ellipsoidal coordinates, geoid heights, height anomalies, etc.):

- GRS80 parameters published by Moritz (2000). Previous publications contain some typos in the normal gravity formulae.
- Atmospheric reduction has to be applied on the (terrestrial and airborne) gravity data.

Global Gravity Model (GGM):

- Since the disturbing potential should be estimated with high-precision, it is proposed to compute (a) the long wavelength component (about d/o < 200...250) using a satellite-only GGM and (b) the short wavelength component (d/o > 200...250) by the combination of terrestrial (airborne, marine and land) gravity data and detailed terrain models.
- The GGM should be at least based on the combination of SLR (satellite laser ranging), GRACE and GOCE data, due to the improvement offered by these data to the long wavelengths of the Earth's gravity field modelling. Suggested models are the latest GOCO releases, i.e., GOCO05s, d/o=280 (Mayer-Gürr and GOCO Team 2015); GOCO06s, d/o=300 (Kvas et al. 2019).
- Although, the use of a satellite-only GGM is preferred, the possibility of using a combined GGM is open (combined means including terrestrial gravity data). It is important that the satellite-only component of the combined model is based on the combination of SLR, GRACE and GOCE data.
- If required, the conversion between the zero-tide system and the tide-free system should be made using:

$$\bar{C}_{20}^{\mathrm{TF}} - \bar{C}_{20}^{\mathrm{ZT}} = 3.11080 \cdot 10^{-8} \times 0.3/\sqrt{5}$$

First-degree terms: The first-degree coefficients ($C_{10} = C_{11} = S_{11} = 0$) are assumed to be zero to align the Earth's centre of masses with the origin of the geometric coordinate system (ITRS/ITRF). In this way, the disturbing potential T is given by (cf. Eq. 2-170 Heiskanen and Moritz 1967):

$$\begin{aligned} T(\vartheta,\lambda) &= T_0 + T_1(\vartheta,\lambda) + \sum_{n=2}^{\infty} T_n(\vartheta,\lambda) \\ \text{with} \quad T_1(\vartheta,\lambda) &= 0 \end{aligned} \tag{4.3}$$

Zero-degree term: The zero-degree term should be dealt with as follows:

- For the disturbing potential (T): The zero-degree term T_0 has to include the difference between the GGM and reference ellipsoid's GM constants (cf. Eq. 2-172 Heiskanen and Moritz 1967):

$$\begin{aligned} T_0 &= \left(GM_{\mathrm{GGM}} - GM_{\mathrm{GRS80}}\right)/r_{\mathrm{P}} = \\ &= \left(3.986004415 \times 10^{14}\,\mathrm{m^3s^{-2}} \right. \\ &\qquad \left. - 3.98600 \times 10^{14}\,\mathrm{m^3s^{-2}}\right)/r_{\mathrm{P}} \end{aligned} \tag{4.4}$$

  with r_P beeing the geocentric radial distance of the computation point P.

- For the quasi-geoid (ζ) or the geoid (N): In addition to the difference between the two GM values, the difference between the reference potential W_0 value adopted by the IHRS and the potential U_0 on the reference ellipsoid has to be considered (cf. the generalised Brun's formula in Eq. 2-178, and also Eq. 2-182 Heiskanen and Moritz 1967):

$$\zeta_0 = \frac{(GM_{\mathrm{GGM}} - GM_{\mathrm{GRS80}})}{r_{\mathrm{P}} \cdot \gamma_{\mathrm{Q}}} - \frac{\Delta W_0}{\gamma_{\mathrm{Q}}} \tag{4.5}$$

$$N_0 = \frac{(GM_{\mathrm{GGM}} - GM_{\mathrm{GRS80}})}{r_{\mathrm{P}_0} \cdot \gamma_{\mathrm{Q}_0}} - \frac{\Delta W_0}{\gamma_{\mathrm{Q}_0}} \tag{4.6}$$

with

$$\begin{aligned}\Delta W_0 &= W_0 - U_0 = \\ &= 62\,636\,853.4\,\mathrm{m^2s^{-2}} - 62\,636\,860.850\,\mathrm{m^2s^{-2}} \\ &= -7.45\,\mathrm{m^2}s^{-2}\end{aligned}$$

Figure 4.1 shows the positions of P, Q, $\mathrm{P_0}$ and $\mathrm{Q_0}$.

As it was stated above that the geoid/quasi-geoid should be consistent with the IHRS reference level W_0 and that GRS80 is to be used as normal gravity field/ellipsoid, it is concluded:

1) To compute the quasi-geoid: compute starting with $n = 2$ and then add Eq. (4.5).
2) To compute the geoid: compute N starting with $n = 2$ and then add Eq. (4.6).

Potential values W_P as IHRS/IHRF coordinates: To determine the potential value W_P at the stations located on the Earth's surface, consistency with the approach used for the estimation of the disturbing potential should be ensured. If the quasi-geoid is computed, the disturbing potential is determined at the point P on the Earth's surface (see Fig. 4.1) and the estimation of W_P is straightforward:

$$W(\mathrm{P}) = U(\mathrm{P}) + T(\mathrm{P}) = U(\mathrm{P}) + \left(T_0 + \sum_{n=2}^{\infty} T_n(\mathrm{P})\right) \tag{4.7}$$

or

$$W(\mathrm{P}) = U(\mathrm{P}) + \gamma\zeta(\mathrm{P}) + \Delta W_0\,. \tag{4.8}$$

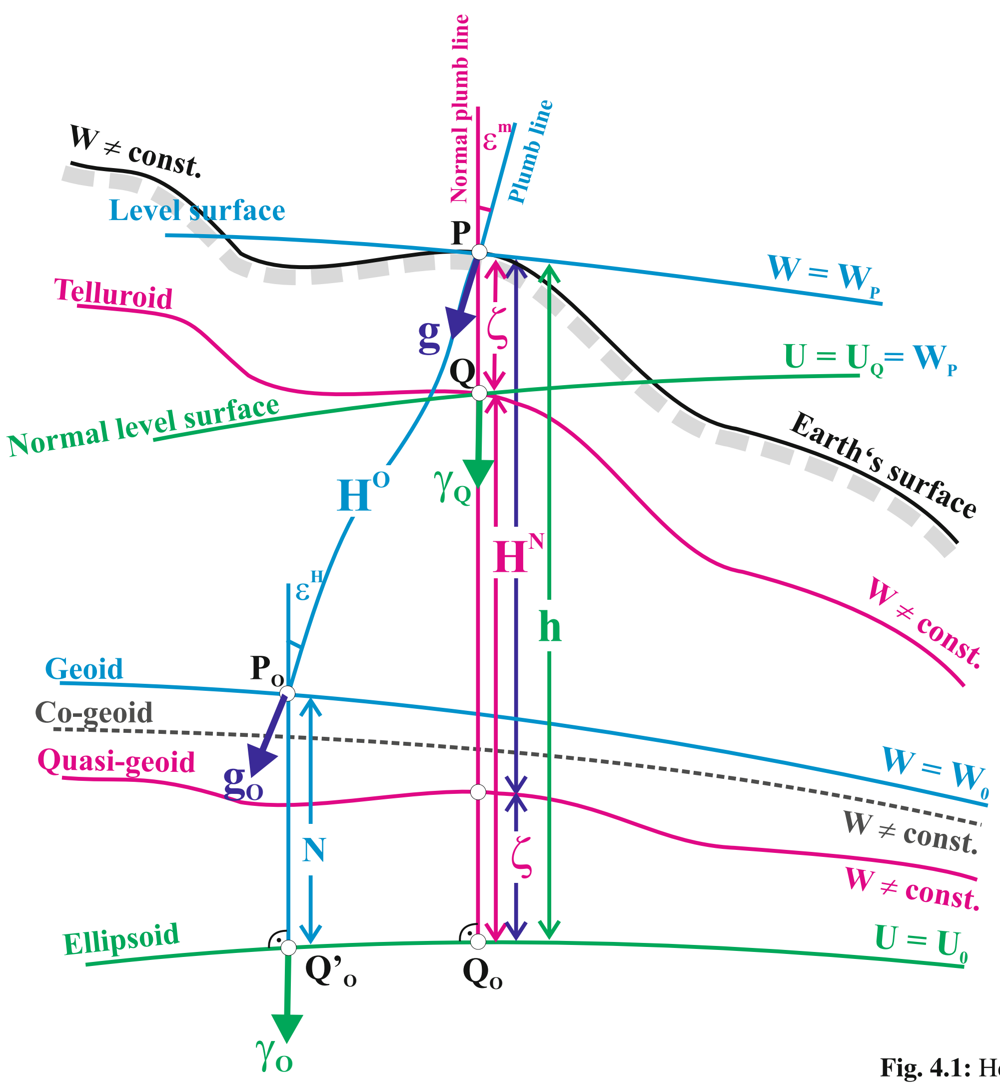


Fig. 4.1: Heights and reference surfaces

When the geoid is computed, the disturbing potential is determined at the point P_0 on the geoid (inside the Earth's topographic masses, see Fig. 4.1) and an upward continuation would be necessary to estimate W_P on the Earth's surface. This upward continuation must be consistent with the hypotheses applied to reduce the gravity values from the Earth's surface to the geoid. Therefore, it is strongly recommended to start from the quasi-geoid or disturbing potential at surface and then to infer the potential values W_P using Eq. (4.7) or (4.8). If the geoid computation is preferred, it would be necessary to transform N to ζ and then to infer the potential values W_P with (4.7) or (4.8). The transformation from N to ζ must be consistent with the hypotheses applied for the geoid computation. As this transformation produces a precision degradation, it is not desired for the computation of the potential values W_P.

As mentioned in Section 4.6.5, these standards will be refined in agreement with the results of the on-going Colorado experiment.

4.6.7 Links to other products

To best exploit the advantages offered by space geodetic techniques, especially in the combination of GNSS positioning and satellite-based (quasi-)geoid models, modern height systems should support with high precision the integration of physical and geometrical coordinates. For that purpose the interaction of the following IAG/GGOS components and products is necessary

GGOS Focus Area Unified Height System: to assess its requirements for the definition and realisation of a unified global vertical reference system.

IAG Commission 1 (Reference Frames): to identify strategies, standards and conventions needed to increase the accuracy of the geometrical heights.

IAG Commission 2 (Gravity Field) and **ISG (International Service for the Geoid)**: to identify strategies, standards and conventions needed to increase the accuracy of the (quasi-)geoid modelling.

IAG Sub-commissions 1.3 (Regional Reference Frames), 2.1 (Gravimetry and Gravity Networks) and 2.4 (Regional Geoid Determination): to assess the detailed characteristics of the existing height systems in order to extent the global vertical reference frame activities to national and regional level.

IERS and **IGS**: to recognise the standards applied for the computation of the geometric vertical coordinates and to align (if necessary) these standards with those outlined/applied by the gravity community.

IGS Working Group Tide Gauge Benchmark Monitoring (TIGA) and **Permanent Service for Mean Sea Level (PSMSL)**: to connect the local height-zero levels to the terrestrial reference frame and to model the sea surface topography at the reference tide gauges.

IGFS and **ICGEM**: to identify the most appropriate global gravity model to compute the long-wavelength components of the global reference surface.

BGI and **IAG Sub-commissions 2.1 (Gravimetry and Gravity Networks) and 2.4 (Regional Geoid Determination)**: to improve the availability of terrestrial (shipborne and airborne) gravity data for the computation of the medium-wavelength components of the global reference surface.

IDEMS: to identify the most appropriate elevation models to estimate the terrain effects in the (quasi-)geoid modelling (short-wavelength components of the global reference surface).

This list is far from being complete and it includes *expected* products, which currently do not exist or have not been considered by some IAG/GGOS components.

4.6.8 Open problems and recommendations

A main result of the Colorado experiment should be a document similar to the IERS conventions; i.e., a sequence of chapters describing the different components to be considered for the realisation of the IHRS and its practical utilisation. Based on these conventions, a first solution for the IHRF should be computed. The aim of this first solution is to evaluate the achievable accuracy under the present conditions (data availability, computation methods, etc.) and to identify key actions to improve the determination of the IHRS/IHRF coordinates. These key actions include an investigation about the best way to establish an IHRS/IHRF element within the IGFS to ensure the maintenance and availability of the IHRF. This implies regular updates of the IHRFyy to take account for new stations, coordinate changes with time, improvements in the estimation of coordinates (more observations, better standards, better models, better computation algorithms, etc.), geodetic products associated to the IHRF (description and metadata), and the organisational and operational infrastructure to ensure the IHRF sustainability.

To improve the standardisation of the existing height systems, it is necessary, among other issues, that meta-data describing the characteristics of the existing height systems be implemented. These meta-data should include for instance:

- epoch and time span applied for the mean sea level introduced as a zero-height;
- changes of the mean sea level and vertical position of the reference tide gauges;
- information about the levelling techniques applied to extend the vertical control through the countries;
- gravity reductions applied to the measured level differences;
- precision of levelling and gravity data;

- epoch and tide system to which the vertical coordinates refer, etc.

When this information is available, it would be possible to transform the existing physical heights in such a way that they can be combined with GNSS positioning and (quasi-)geoid models consistently. For that purpose, it is necessary to involve the national agencies responsible for the maintenance of vertical networks.

Since the vertical datum unification is based on the combination of levelling data (+ gravity reductions), GNSS positioning and (quasi-)geoid modelling, it is convenient to outline the minimal requirements to be satisfied by those stations used for this purpose. For instance, it is well-known that the vertical coordinates derived from GNSS positioning are strongly influenced by systematic errors and physical phenomena that reduce their accuracy considerably. The determination of the level discrepancies between different height systems should be determined including the most precise ellipsoidal heights only; i.e., at ITRF stations and regional densification stations like EPN, SIRGAS, NAREF, etc. These stations must also be connected by spirit levelling to the reference tide gauges; and gravity measurements along the levelling lines must be available for the computation of the corresponding geopotential numbers. Complementarily, the geoid models of high resolution should be estimated in a consistent manner. Currently, the geoid computation is not a unified or standardised procedure, and it is possible to find different geoid models over the same region although they are based on the same input data, i.e., there are as many geoids as computations. In addition, it is usual to compute improved geoid models, if new gravity data and new analysis strategies are available; however, it is not clear how frequently the geoid should be updated.

From the organisational point of view, it is necessary that the IAG/GGOS components named in the previous section precisely outline which products are under their responsibility and how they are generated. As a first step, a description similar to the IERS Conventions should be implemented for each product. The standards outlined by each IAG/GGOS component must be classified into a hierarchical structure, showing which of them have to be followed by everyone, which of them are applicable in geometry or gravity only, which of them are technique-specific, etc. Missing products must be identified and the necessary actions taken for their generation. This procedure has to be extended also to the marine and fluvial areas. At present, the discussion concentrates on the height systems on land areas; but the vertical coordinates on water and ice areas should also refer to the same global unified height system.

Summary of recommendations on height systems

Recommendation 6.1: It is necessary that the IAG/GGOS components involved in the vertical coordinate determination should outline precisely which products are under their responsibility and how they are generated.

Recommendation 6.2: To achieve the standardisation of the existing height systems, it is necessary, among others, that meta-data describing the characteristics of the existing height systems be implemented.

Recommendation 6.3: Since the vertical datum unification is based on the combination of levelling data (+ gravity reductions), GNSS positioning, and (quasi-)geoid modelling, the minimal requirements to be used for stations should be outlined.

Recommendation 6.4: The GGOS Focus Area Unified Height System, the IAG Commission 2 (Gravity Field) and the IGFS should investigate the best way to establish an IHRS/IHRF element within the IGFS to ensure the maintenance and availability of the IHRF and its products.

5 Summary

The GGOS Bureau of Products and Standards (BPS) has compiled an inventory of standards and conventions used for the generation of IAG products. The first version of this document has been published in the Geodesists Handbook 2016. During the last four years, the inventory has been updated to incorporate the changes and new developments concerning standards, conventions and the generation of IAG products. This second version of the document has been prepared for the publication in the Geodesists Handbook 2020.

According to its Terms of Reference, a key activity of the BPS is to assess the standards and conventions adopted and used by IAG and its components for the processing of geometric and gravimetric observations as basis for the generation of IAG products. The work has been performed in cooperation with the IAG Services and the other entities involved in standards and conventions, such as IAU, ISO, CODATA and the UN-GGIM Subcommittee on Geodesy. The overall objective of this inventory is to evaluate the present status concerning standards and geodetic products, to identify gaps and shortcomings, and to provide recommendations for improvements. In this way, the BPS supports IAG in its goal to obtain geodetic products of highest accuracy and consistency.

This second version of the inventory includes an update of the GGOS structure and the BPS activities. It also comprises various updates in the field of standards and conventions, such as the newly released ISO standards by ISO/TC211 covering geographic information and geomatics, the activities of the GGRF Working Group "Data Sharing and Development of Geodetic Standards" within the UN-GGIM Subcommittee on Geodesy, the re-writing/revising of the IERS Conventions initiated by the IERS Conventions Centers, and the recently adopted resolutions by IAG, IUGG and IAU that are relevant for geodetic standards and products. An open problem is the current situation concerning numerical standards including time and tide systems. The fact that various definitions are in use within the geodetic community is a potential source for inconsistencies and even errors of geodetic products. The BPS recommends that these inconsistencies need be resolved and that a new Geodetic Reference System should be developed.

Since 2016, new IERS products have been released for the celestial and terrestrial reference frame as well as for the EOP, namely ICRF3, ITRF2014 and EOP 14C04. Although a significant progress has been achieved compared to the previous realisations, there are still some deficiencies and open problems that are addressed in this inventory, and recommendations are provided to further improve the accuracy and consistency of these products. Concerning GNSS satellite orbits the modelling has been improved and some missing information has been provided by the satellite operators, but there are still some remaining deficiencies. A remarkable progress has been achieved in the field of gravity and geoid related data and products, including the establishment of the IGFS Central Bureau and the development of a dedicated data and products portal based on online applications for the creation of metadata for gravity and geoid data. Finally, the latest developments in the field of height systems and their realisations are reported, open problems are discussed and recommendations towards the realisation of the IHRS are provided.

This inventory will be updated on a regular basis to incorporate the latest developments regarding standards and geodetic products. Thereby, also the ongoing activities of IAG towards the development of new products need to be incorporated in the updates of this inventory.

Glossary

AAM Atmospheric Angular Momentum.
AC Analysis Centre.
ACC Analysis Centre Coordinator.
AGN Active Galactic Nuclei.

BCRS Barycentric Celestial Reference System.
BGI Bureau Gravimétrique International.
BIH Bureau International de l'Heure.
BIPM Bureau International de Poids et Mesures.
BPS GGOS Bureau of Products and Standards.
BSC GGOS Bureau for Standards and Conventions.
BTM Bathymetric Terrain Model.

CAO Cabinet Office, Government of Japan.
CBE Current Best Estimates.
CEOS Committee of Earth Observation Satellites.
CIP Celestial Intermediate Pole.
CIRS Celestial Intermediate Reference System.
CM Centre of Mass.
CODATA Committee on Data for Science and Technology.
CODE Center for Orbit Determination in Europe.
COST-G International Combination Service for Time-variable Gravity Fields.
CPO Celestial Pole Offset.
CSNO China Satellite Navigation Office.
CTRS Conventional Terrestrial Reference System.

DEM Digital Elevation Model.
DGFI-TUM Deutsches Geodätisches Forschungsinstitut, Technische Universität München.
DLR Deutsches Zentrum für Luft- und Raumfahrt.
DOI Digital Object Identifier.
DORIS Doppler Orbit Determination and Radiopositioning Integrated by Satellite.

ECMWF European Centre for Medium-Range Weather Forecasts.
ECOM Empirical CODE Orbit Model.
EGM 2008 Earth Gravitation Model 2008.
EGV Essential Geodetic Variables.
EOP Earth Orientation Parameters.
EOSDIS NASA's Earth Observing System Data and Information System.
EPN EUREF Permanent GNSS Network.
EPOS European Plate Observing System.
ERP Earth Rotation Parameters.
ESA European Space Agency.
EUREF IAG Reference Frame Sub-Commission for Europe.

FCN Free Core Nutation.
FGS Forschungsgruppe Satellitengeodäsie.
FICN Free Inner Core Nutation.
FK5 Fifth Catalogue of Fundamental Stars.
FOC Full Operational Capability.

GCRS Geocentric Celestial Reference System.
GEO Group on Earth Observation.
GEOSS Global Earth Observation System of Systems.
GFZ Helmholtz Centre Potsdam, German Research Centre for Geosciences.
GGIM Global Geospatial Information Management.
GGOS Global Geodetic Observing System.
GGRF Global Geodetic Reference Frame.
GIAC GGOS Inter Agency Committee.
GIS Geographic Information System.
GLONASS Globalnaja nawigazionnaja sputnikowaja sistema.
GMF Global Mapping Function.
GNSS Global Navigation Satellite System.
GPS Global Positioning System.
GPT Global Pressure and Temperature.
GPT2 Global Pressure and Temperature 2.
GRACE Gravity Recovery And Climate Experiment.
GRACE-FO Gravity Recovery And Climate Experiment – Follow On.
GRS Geodetic Reference System.
GRS80 Geodetic Reference System 1980.
GSFC Goddard Space Flight Center.
GSPM GPS Solar Pressure Model.

IAG International Association of Geodesy.
IAGBN International Absolute Gravity Basestation Network.
IAPG Ingenieurinstitut für Astronomische und Physikalische Geodäsie, Technische Universität München.
IAU International Astronomical Union.
ICGEM International Centre for Global Earth Models.
ICRF International Celestial Reference Frame.
ICRF2 Second Realization of the International Celestial Reference Frame.
ICRS International Celestial Reference System.
IDEMS International Digital Elevation Model Service.
IDS International DORIS Service.
IERS International Earth Rotation and Reference Systems Service.
IGETS International Geodynamics and Earth Tide Service.
IGFS International Gravity Field Service.
IGFS CB IGFS Central Bureau.

IGN Institut National de l'Information Géographique et Forestiere, France.
IGS International GNSS Service.
IGSN71 International Gravity Standardization Net 1971.
IGSO Inclined Geo-Synchronous Earth Orbit.
IHRF International Height Reference Frame.
IHRS International Height Reference System.
ILRS International Laser Ranging Service.
IOV In-Orbit Validation.
IRNSS Indian Regional Navigation Satellite System.
ISC International Science Council.
ISG International Service for the Geoid.
ISO International Organization for Standardization.
ITRF International Terrestrial Reference Frame.
ITRS International Terrestrial Reference System.
IUGG International Union of Geodesy and Geophysics.
IVS International VLBI Service for Geodesy and Astrometry.

JPL Jet Propulsion Laboratory.

LEO Low Earth Orbiter.
LLR Lunar Laser Ranging.
LOD Length of Day.

MEO Medium Earth Orbit.
MGEX Multi-GNSS Pilot Project.
MGWG Multi-GNSS Working Group.

NAGU Notice Advisory to Galileo Users.
NAGU Notice Advisory to GLONASS Users.
NANU Notice Advisory to NAVSTAR Users.
NAQU Notice Advisory to QZSS Users.
NAREF North American Reference Frame.
NASA National Aeronautics and Space Administration.
NAVGEM US Navy's Global Environmental Model.
NCEP National Centers for Environment Prediction.
NGS National Geodetic Survey.
NIST National Institute of Standards and Technology.
NNR No-Net-Rotation.
NSFA IAU Division A Working Group Numerical Standards for Fundamental Astronomy.

OAM Oceanic Angular Momentum.
OGC Open Geospatial Consortium.
OHI Operational History Information.
OMCT Ocean Model for Circulation and Tides.

PCO Phase Centre Offset.
PCV Phase Centre Variation.
PREM Preliminary Reference Earth Model.
PSMSL Permanent Service for Mean Sea Level.

QZSS Quasi-Zenith Satellite System.

SBAS Space Based Augmentation System.
SCoG Subcommittee on Geodesy (UN-GGIM).
SI International System of Units.
SINEX Solution INdependent EXchange format.
SIRGAS Sistema de Referencia Geocéntrico para las Américas (Geocentric Reference Frame for the Americas).
SLR Satellite Laser Ranging.
SOFA Standards of Fundamental Astronomy.
SRP Solar Radiation Pressure.

TCG Geocentric Coordinate Time.
TDB Barycentric Dynamical Time.
TEC Total Electron Content.
TIGA Tide Gauge Benchmark Monitoring.
TIRS Terrestrial Intermediate Reference System.
TRF Terrestrial Reference Frame.
TRS Terrestrial Reference System.
TT Terrestrial Time.

UN United Nations.
UN-GGIM UN Committee of Experts on Global Geospatial Information Management.
USNO United States Naval Observatory.
UTC Coordinated Universal Time.

VLBI Very Long Baseline Interferometry.

WGM World Gravity Map.
WGRF IAU Working Group on Reference Frames.

ZTD Zenith Total Delay.

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International Earth Rotation and Reference Systems Service (IERS)

Chair of the Directing Board: **Brian Luzum** (USA)
Director of the Central Bureau: **Daniela Thaller** (Germany)

https://www.iers.org/

Development

The IERS was established as the International Earth Rotation Service in 1987 by the International Astronomical Union and the International Union of Geodesy and Geophysics, and it began operation on 1 January 1988. Since 2001, the IERS works in a new organizational structure; in 2003, the new name of the Service, without changing its abbreviation, was adopted. The IERS is a Regular Member of the ICSU World Data System (WDS) and an Associate Member of the International Committee on Global Navigation Satellite Systems (ICG).

Objectives

The primary objectives of the IERS are to serve the astronomical, geodetic and geophysical communities by providing the following:

- The International Celestial Reference System (ICRS) and its realization, the International Celestial Reference Frame (ICRF);
- The International Terrestrial Reference System (ITRS) and its realization, the International Terrestrial Reference Frame (ITRF);
- Earth orientation parameters required to study earth orientation variations and to transform between the ICRF and the ITRF;
- Geophysical data to interpret time/space variations in the ICRF, ITRF or earth orientation parameters, and model such variations;
- Standards, constants and models (i.e., conventions) encouraging international adherence.

Products

IERS collects, archives and distributes products to satisfy the objectives of a wide range of applications, research and experimentation. These products include the following:

- International Celestial Reference Frame;
- International Terrestrial Reference Frame;
- Final daily earth orientation data updated monthly;
- Rapid service estimates of near real-time earth orientation data and their predictions updated four times per day;
- Announcements of the differences between astronomical and civil time for time distribution by radio stations;
- Leap second announcements;
- Products related to global geophysical fluids such as mass and angular momentum distribution;
- Annual reports and technical notes on conventions and other topics;
- Long-term earth orientation information.

The accuracies of these products are sufficient to support current scientific and technical objectives including the following:

- Fundamental astronomical and geodetic reference systems;
- Monitoring and modeling earth rotation/orientation;
- Monitoring and modeling deformations of the solid earth;
- Monitoring mass variations in the geophysical fluids, including the atmosphere and the hydrosphere;
- Artificial satellite orbit determination;
- Geophysical and atmospheric research, studies of dynamical interactions between geophysical fluids and the solid earth;
- Space navigation.

Structure

The IERS accomplishes its mission through the following components:

- Technique Centers: International GNSS Service, International Laser Ranging Service, International VLBI Service, and International DORIS Service;
- Product Centers: Earth Orientation Center, Rapid Service/Prediction Center, Conventions Center, ICRS Center, ITRS Center, and Global Geophysical Fluids Center with Special Bureaus for the Atmosphere, for the Oceans, for Hydrology, and for Combination;
- ITRS Combination Centers at Deutsches Geodätisches Forschungsinstitut at TU München (DGFI-TUM), Institut Géographique National (IGN), Jet Propulsion Laboratory (JPL);
- Analysis Coordinator;
- Central Bureau;
- Directing Board;
- Working Groups: WG on Site Survey and Co-location, WG on SINEX Format, WG on the Consistent Realization of TRF, CRF, and EOP.

Some of these components (e.g., Technique Centers) may be autonomous operations, structurally independent from IERS, but which cooperate with the IERS. A participating organization may also function as one or several of these components.

IERS Directing Board, as of June 2020

Zuheir Altamimi (France),	ITRS Center Representative
Christian Bizouard (France)	Earth Orientation Center Representative
Sigrid Böhm (Austria),	IVS Representative
Jean-Paul Boy (France),	GGFC Representative
Aleksander Brzezinski (Poland),	IAU Representative
Hugues Capdeville (France)	IDS Representative
Rolf Dach (Switzerland),	IGS Representative
Richard Gross (USA),	GGOS Representative
Rüdiger Haas (Sweden),	IVS Representative
Christine Hackman (USA),	Rapid Service/Prediction Center Representative
Robert Heinkelmann (Germany),	Analysis Coordinator
Thomas Herring (USA),	IAG / IUGG Representative
Brian Luzum (USA),	Chair of the IERS Directing Board
Chuck Meertens (USA),	IGS Representative
Erricos C. Pavlis (USA),	ILRS Representative
Jérôme Saunier (France),	IDS Representative
Jean Souchay (France),	ICRS Center Representative
Nick Stamatakos (USA),	Conventions Center Representative
Daniela Thaller (Germany)	Director of the Central Bureau
Jean-Marie Torre (France),	ILRS Representative

International DORIS Service (IDS)

Chair of the Governing Board: **Frank Lemoie** (U.S.A.)
Director of the Central Bureau: **Laurent Soudarin** (France)

https://ids-doris.org/

Terms of Reference (ToR)

Accepted by the IAG Executive Committee at the XXIIIth IUGG General Assembly, Sapporo, Japan, July 1, 2003. Revised by the IDS ToR Working Group, and approved by the IDS Governing Board on, June 23, 2011.

Addenda issued by the IDS Governing Board, approved by the IAG Executive Committee at the XXVIth IUGG General Assembly, Prague, Czech Republic, June 26, 2015

Introduction

The DORIS (Doppler Orbit determination and Radio-positioning Integrated on Satellite) system for satellite orbit determination and precise positioning was developed by the Centre National d'Etudes Spatiales (CNES) in conjunction with the Institut Géographique National (IGN) and the Groupe de Recherche de Géodesie Spatiale (GRGS).

A proof of concept for the International DORIS Service (IDS) was conducted through a pilot phase prior to the establishment of the International DORIS Experiment in 1999 by the International Association of Geodesy (IAG). The IDS formally began on July 1, 2003 after the IAG official approval at the IUGG General Assembly in Sapporo. The IDS is an IAG Service and operates in close cooperation with the International Earth rotation and Reference systems Service (IERS).

The IDS Mission

The primary objective of the IDS is to provide a service to support geodetic and geophysical research activities through DORIS data and derived products.

The IDS collects, archives and distributes DORIS observation data sets of sufficient accuracy to satisfy the objectives of a wide range of applications and experimentations. From these data sets the following products are derived:

- Coordinates and velocities of the IDS tracking stations
- Geocenter and scale of the Terrestrial Reference Frame
- High accuracy ephemerides of the DORIS satellites
- Earth orientation parameters (EOPs)

The accuracies of these products are sufficient to support current scientific objectives including:

- Realization of global accessibility to and the improvement of the International Terrestrial Reference Frame (ITRF)
- Monitoring deformations of the solid Earth
- Monitoring crustal deformation at tide gauges
- Monitoring variations in the hydrosphere (sea level, ice-sheets, etc.)
- Orbit determination for scientific satellites

The IDS Organization

The IDS accomplishes its mission through the following components:

- Satellites carrying a DORIS receiver
- Network of tracking stations
- Data Centers
- Analysis Centers, Associate Analysis Centers and Analysis Coordinator
- Combination Center
- Working Groups
- Central Bureau
- Governing Board

Satellites Carrying a DORIS Receiver

Since July 2003, the CNES and the European Space Agency (ESA) have provided DORIS data to the IDS. Data from additional agencies are expected and welcome. DORIS receivers are flown on LEO satellites for precise orbit determination as well as for geodetic applications. Satellites with DORIS receivers are listed on the IDS website at https://ids-doris.org/.

A representative of the DORIS system serves as a voting member of the Governing Board.

Tab. 1 DORIS data available at IDS Data Centers (Jan. 2020)

Satellite	Start	End	Type
SPOT-2	31-MAR-90 04-NOV-92	04-JUL-90 15-JUL-09	Remote sensing
TOPEX/ Poseidon	25-SEP-92	01-NOV-94	Remote sensing
SPOT-3	01-FEB-94	09-NOV-96	Remote sensing
SPOT-4	01-MAY-98	24-JUN-13	Remote sensing
SPOT-5	11-JUN-02	11-DEC-15	Remote sensing
Jason-1	15-JAN-02	21-JUN-13	Altimetry
ENVISAT	13-JUN-02	08-APR-12	Altimetry, Environment
Jason-2	12-JUL-08	10-OCT-19	Altimetry
Cryosat-2	30-MAY-10	–	Altimetry
HY-2A	1-OCT-11	–	Altimetry
SARAL	14-MAR-13	–	Altimetry
Jason-3	17-JUN-16	–	Altimetry
SENTINEL-3A	16-FEB-16	–	Altimetry
SENTINEL-3B	25-APR-18	–	Altimetry

Network of Tracking Stations

The IDS network is composed of DORIS permanent tracking stations located at host institutions and maintained by the IGN. A list of the sites (past and present) is included on the IDS website at https://ids-doris.org/.

The network also includes additional DORIS stations proposed by the IDS to observe during specific campaigns of scientific interest. A representative of the Network serves as a voting member of the Governing Board.

Data Centers

The Data Centers are in direct contact with the CNES, which provides the DORIS data. The Data Centers archive the DORIS data, derived products, and ancillary information required to process these data.

A representative of the Data Centers serves as a voting member of the Governing Board.

Analysis Centers, Associate Analysis Centers and Analysis Coordinator

The Analysis Centers (ACs) are committed to provide at least one of the above IDS products on a regular basis. Expertise in DORIS data analysis and operational capability are essential factors in the selection of Analysis Centers. ACs adhere to IDS recommendations for the creation of high-quality products and their timely archiving and distribution. Currently, only groups providing IDS products routinely may be considered as Analysis Centers.

Tab. 2 List of IDS Analysis Centers and Associate Analysis Centers (January 2020)

Analysis Center	Country	Software
ESA/ESOC	Germany	NAPEOS
Geod. Observatory Pecny	Czech Rep.	Bernese
NASA/GSFC	USA	GEODYN
IGN	France	GIPSY/OASIS
INASAN	Russia	GIPSY/OASIS
CNES/CLS	France	GINS/DYNAMO
Associate Analysis Center		
GFZ	Germany	EPOS-OC
CNES/POD	France	Zoom
TU Delft	Netherlands	
DGFI-TUM	Germany	DOGS

The Analysis Coordinator assists the Analysis Centers and monitors their activities to ensure that the IDS objectives are carried out. The Analysis Coordinator, working with the Analysis Centers, is expected to provide quality control, performance evaluation, and continued development of appropriate analysis standards. The Analysis Coordinator, with the support of the Combination Center, is also responsible for the appropriate combination of the Analysis Centers products into a single set of prescribed data products.

The Analysis Coordinator and a representative of the Analysis Centers serve as voting members of the Governing Board.

Associate Analysis Centers provide specialized or derived products, not necessarily at regular intervals (such as precise orbits, station positions, Earth Orientation Parameters, ionospheric products, tropospheric delays, or any scientific data products of a mission specific nature). They are recognized as such by the Governing Board, upon recommendation of the Analysis Coordinator. The Associate Analysis Centers are encouraged to present their results at IDS meetings and to submit their final results in IDS Data Centers for dissemination to researchers and other users. An Associated Analysis Center (AAC) may become an Analysis Center after demonstrating its expertise and operational capability during a test period.

Combination Center

The IDS appoints a Combination Center (CC) to combine individual AC solutions and to generate IDS data products for submission to the IERS for the formulation of the periodic update of the ITRF and other geodetic products. The CC is selected by the Governing Board every four years through a Call for Participation initiated six months prior to the end of the current CC term. Interested centers submit proposals outlining their plan for operation of the CC and the resources that they will commit.

A representative of the Combination Center serves as a voting member of the Governing Board.

Working Groups

IDS Working Groups provide expertise on particular topics related to the IDS components and on development of particular IDS product(s) or service(s) relying on the IDS infrastructure.

All Working Groups are created when needed and retired by the IDS Governing Board when their work has been completed or they are no longer needed. Each Working Group must develop a charter that includes a mandate, a list of specific tasks, a schedule, and an identified Chairperson.

The Chairpersons of the Working Groups are non-voting members of the IDS Governing Board (see below).

Central Bureau

The Central Bureau (CB) is the executive arm of the IDS Governing Board and as such is responsible for the general management of the IDS consistent with the directives, policies and priorities set by the Governing Board.

In this role the CB, within available resources, coordinates IDS activities, facilitates communications, maintains documentation, and organizes reports, meetings, and workshops. The CB responds to external inquiries about the IDS, promotes the use of IDS data and products, and coordinates interactions with other services, including the IERS.

The CB supports the Combination Center in combining the various Analysis Centers products and providing all information necessary to validate the final combined products.

The CB operates the information system for the IDS and produces the IDS Annual Reports and IDS Associates directory. The CB coordinates the publication of other documents required for the satisfactory planning and day-to-day operation of the Service, including standards and specifications regarding the performance, functionality and configuration requirements of all Service elements.

Although the Chairperson of the Governing Board is the official representative of the IDS to external organizations, the CB, consistent with the directives established by the Governing Board, is responsible for the day-to-day liaison with such organizations.

The long-term function of the IDS is assured through redundancy and emergency contingency plan for all of its components except for the CB. The Central Bureau serves for a term of four years. One year prior to the end of each term, the GB formally reviews the performance of the Central Bureau. At the behest of the GB, the CB may be asked to reconfirm its commitment to serve another four years. If the CB agrees, it submits a proposal for GB approval. If the CB declines or if the GB chooses to change CB operators, the GB announces a Call for Proposals for a new IDS Central Bureau to take over responsibilities including a six-month transition phase with the outgoing Central Bureau.

In summary, the Central Bureau performs primarily a long-term coordination role to ensure that IDS participants contribute to the Service in a consistent and harmonious manner and adhere to IDS standards.

The Director of the Central Bureau serves as a voting member of the Governing Board.

Governing Board

The principal role of the Governing Board (GB) is to set policy and to exercise broad oversight of all IDS functions and components. It also controls general activities of the Service, including restructuring, when appropriate, to maintain Service efficiency and reliability.

The Governing Board (GB) consists of eleven voting members and a number of nonvoting members. The membership is chosen to try to strike the right balance between project specialists and the general community. The voting membership of the GB is distributed as follows:

Elected by IDS Associates (see below):	
Analysis Centers' representative:	1
Data Centers' representative	1
Analysis Coordinator:	1
Members-at-Large:	2
Appointed members:	
Director of the Central Bureau:	1
IERS representative to IDS:	1
IAG representative to IDS:	1
Combination Center representative:	1
DORIS System representative (CNES):	1
Network representative (IGN):	1
Total number of voting members:	11

During their mandate, the Working Group chairpersons are GB members with voice but without vote.

The elected members have staggered four-year terms, with elections every two years. There is no limit to the number of terms that a person may serve, however he or she may serve only two terms consecutively as an elected member. The Analysis Center representative, the Data Center representative, and one Member-at-Large are elected during the first two-year election. The Analysis Coordinator and the other Member-at-Large are elected in the second two-year election. Although no formula is prescribed, efforts should be made to keep the GB membership properly balanced with regard to supporting organizations and geographic representation.

Members of the GB become IAG Fellows with the appropriate rights and privileges, as described on the IAG website, after an initial two-year period.

Composition of the IDS Governing Board (January 2020):

Claudio Abbondanza, NASA/JPL, USA, Member at Large
Hughes Capdeville, CLS, France, Analysis Coordination
Petr Štěpánek, Geod. Observatory Pecny, Czech Rep., Analysis Coord.
Denise Dettmering, DGFI/TUM, Germany, Member at Large
Pascale Ferrage, CNES, France, System Representative
Frank Lemoine (Chair) NASA/GSFC, Analysis Center Representative
Brian Luzum, GSFC, USA, IERS Representative
Guilhem Moreaux CLS, France, Combination Center Repr.
Patrick Michael, GSFC, USA, Data Flow Coordinator
Ernst Schrama, TU Delft, The Netherlands, IAG Representative
Jérôme Saunier, IGN, France, Network Representative
Laurent Soudarin, CLS, Director of Central Bureau

GB Elections

The GB elects a Chairperson from its members to serve a term of four years with the possibility of re-election for one additional term. The Chairperson does not vote on GB decisions, except in the case of a tie. The Chairperson is the official representative of the IDS to external organizations.

Five members of the GB are elected by the IDS Associates. A nominating committee conducts the elections for membership on the IDS Governing Board. The nominating committee consists of three members. The Chair of the nominating committee is appointed by the Chair of the GB, and must be a member of the GB not currently up for re-election. The GB chooses the remaining two members of the nominating committee from the list of IDS Associates.

The nominating committee solicits nominations from the IDS Associates for each position to be filled; at least two candidates are required for each position. The Central Bureau runs the election. All IDS Associates are eligible to vote. Election is by a simple majority of votes received for each position. The two Member-at-Large positions are filled by the two candidates receiving the most votes; a vote by the GB will resolve any situation of a tie.

Appointed Members

The IAG and IERS representatives to the IDS Governing Board are appointed by the IAG Executive Committee and by the IERS Directing Board, respectively, for a maximum of two four-year terms. The DORIS System representative and the Network representative are appointed by CNES and IGN, respectively, for four-year terms without limitation. The Director of the Central Bureau and the Combination Center representative are the two other appointed members.

In case of a resignation from the Governing Board, the CB, after consulting with the appropriate IDS components, nominates a replacement candidate for election by the GB. The replacement will serve until the end of the term of the resigned Board member.

GB Decisions

Most decisions at GB meetings are to be made by consensus or by a simple majority vote of the voting members present, provided that there is a quorum consisting of at least six voting members of the GB. GB decisions can be made through email or other correspondence by a majority vote of the GB voting membership. Changes in the IDS Terms of Reference and

Chairperson of the GB can only be made by a 2/3 majority of the members of the GB, i.e., by seven or more votes.

GB Meetings

The Board shall meet at least annually and at such other times as shall be considered appropriate by the Chairperson or at the request of three members. The Central Bureau provides the secretariat of the GB.

IDS representatives to the IERS and the IAG

Through the existing reciprocity agreement between the IDS and the IERS, the IDS Analysis Coordinator serves as the DORIS Technique Center representative to IERS, and as such, subject to Governing Board approval, is a member of the IERS Directing Board (together with another person selected by the IDS Governing Board). This arrangement ensures full cooperation between the two services.

IDS Associates

IDS Associates are persons representing organizations that participate in any of the IDS components. A participating institution can submit a person s name, email, and primary IDS function in its organization to the Central Bureau for application to become an IDS Associate, with a limit of ten. The Governing Board approves all memberships. The Governing Board reserves the right to appoint additional associates who do not participate in any IDS components but who contribute significantly to the IDS or whose activities rely on DORIS data and products. Such names are nominated directly by the IDS GB.

The Central Bureau maintains the current list of IDS Associates and makes the list available on the IDS website.

IDS Associates vote for the incoming Analysis Centers' representative, the Data Centers' representative, the Analysis Coordinator, and the Members-at-Large representatives as members of the GB.

The GB must approve the list of IDS Associates eligible for voting in the elections at least three months prior to the election process. For the purposes of the election, current and former GB members are also considered IDS Associates.

IDS Associates are considered IAG Affiliates.

IDS and DORIS quick reference list

1. **IDS website**
   https://ids-doris.org/
2. **Contacts**
   Central Bureau ids.central.bureau@ids-doris.org
   Governing Board ids.governing.board@ids-doris.org
3. **Data Centers**
   CDDIS: ftp://cddis.gsfc.nasa.gov/doris/
   IGN: ftp://doris.ensg.eu and ftp://doris.ign.fr
4. **Tables of Data and Products**
   https://ids-doris.org/ids/data-products/tables-of-data-products.html
5. **IDS web service**
   https://ids-doris.org/webservice
   DOR-O-T for DORis Online Tools (pronounced in French like the given name Dorothée) is the IDS web service developed to promote the use of the DORIS products. The current version of the service provides tools to browse time series in an interactive and intuitive way, and a network viewer.
6. **Citation**
   The following article is suggested for citation in papers and presentations that rely on DORIS data and results:
   Willis, P.; Lemoine, F.G.; Moreaux, G.; Soudarin, L.; Ferrage, P.; Ries, J.; Otten, M.; Saunier, J.; Noll, C.; Biancale, R.; Luzum, B., 2016. The International DORIS Service (IDS), recent developments in preparation for ITRF2013, IAG SYMPOSIA SERIES, 143, 631-639, DOI: 10.1007/1345_2015_164

7. **DORISmail**
The DORIS mail service is used to send information of general interest to the DORIS community. To send a DORISMail, use the following address: dorismail@ids-doris.org
8. **List of the documentation**
It gives a table compiling links to the various pages providing documents, grouped in four categories: DORIS system components; IDS information system; Publications, presentations; Documents
https://ids-doris.org/ids/reports-mails/documentation.html
9. **List of presentations given at DORIS or IDS meetings**
Full list of presentations given at DORIS or IDS meetings with the corresponding access links
https://ids-doris.org/ids/reports-mails/meeting-presentations.html
10. **List of documents and links to discover the DORIS system**
https://ids-doris.org/analysis-coordination/documents-related-to-data-analysis.html
11. **List of DORIS publications in international peer-reviewed journals**
https://ids-doris.org/ids/reports-mails/doris-bibliography/peer-reviewed-journals.html
12. **Overview of the DORIS system**
https://www.aviso.altimetry.fr/en/techniques/doris.html
13. **Overview of the DORIS satellite constellation**
https://ids-doris.org/doris-system/satellites.html
14. **Site logs**
DORIS stations description forms and pictures from the DORIS installation and maintenance department:
https://ids-doris.org/doris-system/tracking-network/site-logs.html
15. **Virtual tour of the DORIS network with Google Earth**
Download the file at https://ids-doris.org/doris-system/tracking-network/network-on-google-earth.html and visit the DORIS sites all around the world.
16. **IDS video channel**
Videos of the DORIS-equipped satellites in orbit
https://www.youtube.com/channel/UCiz6QkabRioCP6uEjkKtMKg
17. **IDS Newsletters**
Find all the issues published in color with live links on the IDS website
https://ids-doris.org/ids/reports-mails/newsletter.html
18. **Photo Gallery**
https://ids-doris.org/ids/gallery.html

IDS

International GNSS Service (IGS)

IGS INTERNATIONAL GNSS SERVICE

Chair of the Governing Board: **Gary Johnston** (Australia)
Director of the Central Bureau: **Allison Craddock** (USA)

http://www.igs.org/

Background

For over twenty-five years, the International Global Navigation Satellite System (GNSS) Service (IGS) has carried out its mission to advocate for and provide freely and openly available high-precision GNSS data and products. IGS was first approved by its parent organization, the International Association of Geodesy (IAG), at a scientific meeting in Beijing, China, in August of 1993. A quarter century later, the IGS community gathered for a workshop in Wuhan, China, in October/November 2018 to blaze a path to Multi-GNSS through global collaboration.

The Mission of the IGS is to "provide on an openly available basis, the highest-quality GNSS data, products, services in support of the terrestrial reference frame; Earth observation and research; Positioning, Navigation and Timing (PNT); and other applications that benefit the scientific community and society."

In 2019, the IGS adopted an official slogan: "Providing openly available GNSS data and products that benefit science and society," as well as an official organizational vision: "A better understanding of the Earth through the application of GNSS."

Community Collaboration

At the heart of the IGS is a strong culture of sharing expertise, infrastructure, and other resources for the purpose of encouraging global best practices for developing and delivering GNSS data and products all over the world. The collaborative nature of the IGS community, which as of 2019 includes over 140 GNSS stakeholder organizations from 45 countries leverages this diversity to integrate and make full use of all available GNSS technologies while promoting further innovation. Over 15,000 product users, some of whom comprise the backbone of the worldwide geodetic community, ensure that new technologies and systems are integrated into routine IGS products. Responsive to this innovation, the IGS develops and publicly releases standards, guidelines, and conventions for the collection and use of GNSS data and products. The IGS strives to maintain an international federation with committed contributions from its members. To view the list of IGS Governing Board members, please visit: http://www.igs.org/about/gb

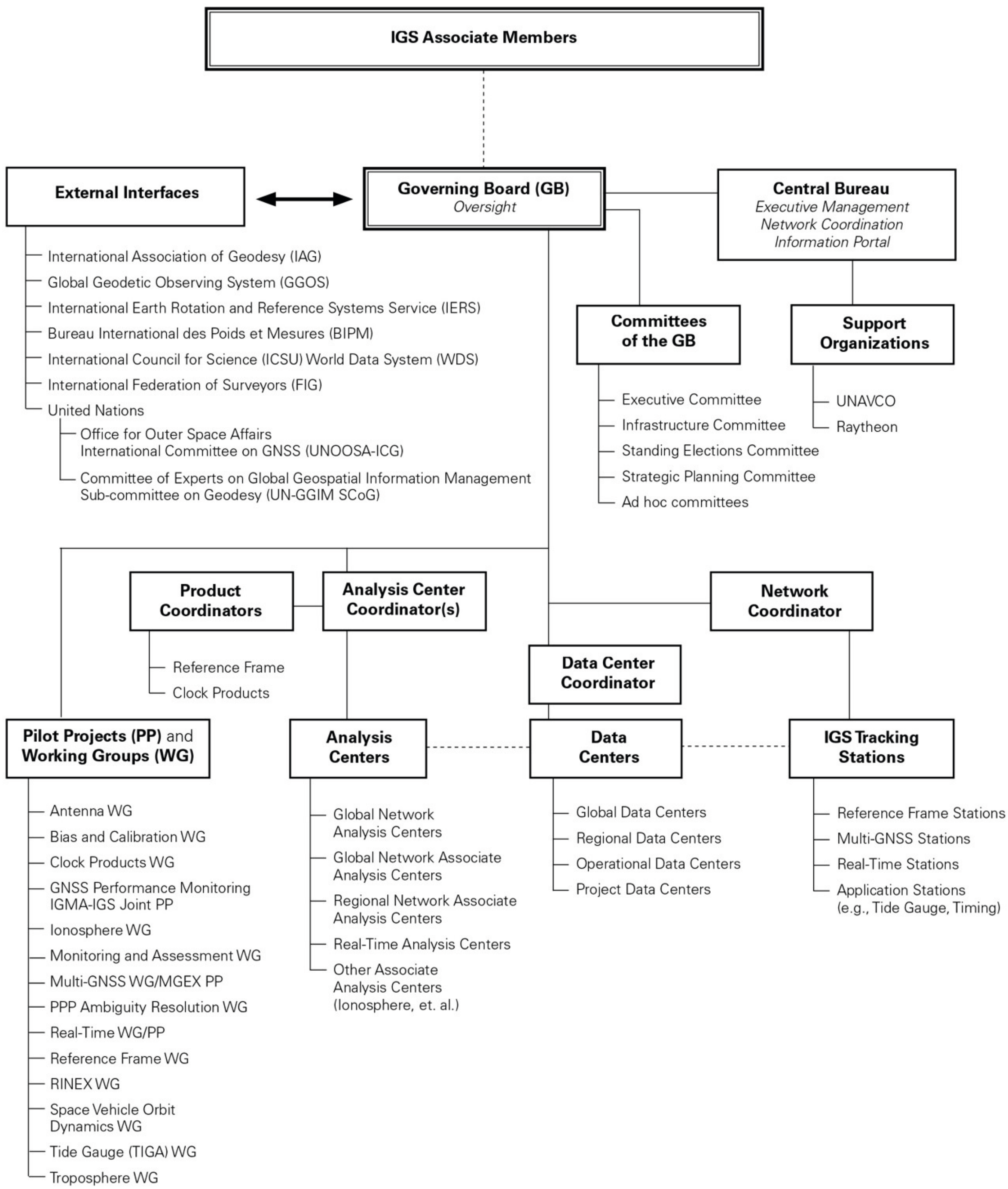
Underpinning Observing Systems and Reference Frames

The IGS is a critical component of the IAG's Global Geodetic Observing System (GGOS), where it facilitates cost-effective geometrical linkages with and among other precise geodetic observing techniques, including: Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), and Doppler Orbitography and Radio Positioning Integrated by Satellite (DORIS). These linkages are fundamental to generating and accessing the International Terrestrial Reference Frame (ITRF).

Engagement with the United Nations

IGS engages with diverse organizations that have an interest in geodetic applications of GNSS. Notably, the IGS has supported the development of the Global Geodetic Reference Frame (GGRF) resolution, roadmap, and implementation plan within the United Nations (UN) Global Geospatial Information Management (GGIM) Committee of Experts (http://ggim.un.org). IGS also participates in the United Nations Office for Outer Space Affairs (UNOOSA) International Committee on GNSS (ICG).

IGS Structure and Association with International Scientific Organizations, as of 2020



Data and Analysis Centers

The IGS ensures high reliability by building redundancy into all its components. Critical to this activity are three categories of data center – operational, regional, and global. At the "ground level" are operational data centers, which are in direct contact with IGS tracking sites, and are responsible for such efforts as station monitoring and local archiving of GNSS data. Operational data centers also validate, format, exchange, and compress data. Regional data centers then collect tracking data from multiple operational data centers or stations, maintaining a local archive and providing online access to their data.

The six global data centers (Crustal Dynamics Data Information System, Scripps Institution of Oceanography, European Space Agency /ESAC, Korean Astronomy and Space Science Institute, Institut National de l'Information Géographique et Forestière, and Wuhan University) receive, retrieve, archive and provide online access to tracking data from operational and regional data centers. The Data Center Coordinator ensures coordination among data centers, as well as global data centers archiving and backing up IGS data and products, and maintaining a balance of data holdings across the IGS network.

Analysis centers then receive and process tracking data from one or more data centers for the purpose of generating IGS products, including satellite ephemerides, Earth rotation parameters, station coordinates, and clock information. These products are produced in ultra-rapid, rapid, final, and reprocessed versions for each analysis center.

Associate analysis centers produce specialized products, including ionospheric information, tropospheric parameters, or station coordinates and velocities for global and regional subnetworks. Regional and global network associate analysis centers complement this work as new capabilities and products emerge within the IGS.

Products from each analysis center are then combined into a single set of orbit and clock products by the Analysis Center Coordinator, who monitors and assists the activities of analysis centers to ensure IGS standards for quality control, performance evaluation, and analysis are successfully executed. The Analysis Center Coordinator also regularly collaborates with the International Earth Rotation and Reference System Service (IERS) on behalf of the IGS.

Growing a Multi-GNSS IGS Network

The foundation of the IGS is a global network of over 500 permanent and continuously operating stations of geodetic quality. These stations track signals from GPS, and increasingly also track signals from GLONASS, Galileo, BeiDou, QZSS, NavIC (IRNSS) as well as space-based augmentation systems (SBAS). As of late 2019, the IGS has 506 Stations, of which 308 are Multi-GNSS stations, and 259 Real-time stations. Central Bureau collaboration with the Infrastructure Committee ensures appropriate and timely addition and decommissioning of stations, along with collaboration with the Antenna Working Group for regular changes to station antennas and rcvr_ant.tab file. The percentage of multi-GNSS capable IGS network is expected to grow in the coming years.

The IGS Multi-GNSS Experiment (MGEX) was founded in 2012 to build a network of GNSS tracking stations, characterize the space segment and user equipment, develop theory and data-processing tools, and generate data products for emerging satellite systems. The stations within its network contain a diverse assortment of receiver and antenna equipment that are recognized and characterized by the IGS in equipment description files. Other than GPS and GLONASS, no combination process has yet been implemented within IGS for precise orbit and clock products of the other, newer, constellations. Despite this, inter-comparison among analysis centers, as well as utilizing Satellite Laser Ranging (SLR), has been used to assess the precision or accuracy for various products.

The growing role of multi-GNSS within the IGS network was benchmarked by the transition of MGEX to official IGS Project status in 2016. For the sake of consistency, and as a nod to its heritage, use of the acronym "MGEX" has been retained. MGEX and its associated Multi-GNSS Working Group recently published a comprehensive paper detailing its achievements in the last five years, future prospects, and challenges. The article, published in Advances in Space Research, Volume 59, Issue 7, 1 April 2017, Pages 1671–1697, discusses the multi-GNSS products derived from the IGS monitoring station network as well as progress made within the MGEX Project to include BeiDou, Galileo, and QZSS for precise point positioning, atmospheric research, and other applications.

Further improvements are expected through better characterization of spacecraft and respective refinements of radiation pressure models, antenna phase center variations, and other effects. In response to this, the Multi-GNSS Working Group released a White Paper, titled "Satellite and Operations Information for Generation of Precise GNSS Orbit and Clock Products." The paper discusses the parameters needed to ensure the highest possible performance of IGS products for all constellations and clearly articulates the need for open provision of satellite and certain other operations information by the GNSS providers.

A Multi-GNSS Future

Though the accuracy of current IGS multi-GNSS products lags standard IGS products for GPS and GLONASS, multi-GNSS paves the way for complete exploitation of new signals and constellations in navigation, surveying, geodesy, and remote sensing. For complete, current information about MGEX, please visit the MGEX part of the IGS website: http://mgex.igs.org/.

As it enters its second quarter-century, the IGS is evolving into a truly multi-GNSS service. In response to ever-growing applications for precise GNSS data as a public utility, the IGS conducts regular reviews of its activities, products, and services. The IGS also works with ICG to develop common understandings of the requirements for system monitoring through a joint pilot project with the ICG's International GNSS Monitoring and Assessment (IGMA) subgroup.

IGS also looks outward to other techniques through its participation in the IAG's GGOS, which has illuminated how SLR observations to GNSS satellites, as well as GNSS observation of non-GNSS satellites, has a key role to play in improving our understanding of observational errors and thus drive further improvement of IGS products.

International Laser Ranging Service (ILRS)

Chairman of the Governing Board: **Toshimichi Otsubo** (Japan)
Director of the Central Bureau: **Michael Pearlman** (USA)
Secretary of the Central Bureau: **Carey Noll** (USA)
Analysis Coordinator: **Erricos C. Pavlis** (USA)

http://ilrs.gsfc.nasa.gov/

Development

Satellite Laser Ranging (SLR) was established in the mid-1960s, with early ground system developments by NASA, SAO, and CNES. Early US and French satellites provided laser targets that were used mainly for inter-comparison with other tracking systems, refinement of orbit determination techniques, and as input to the development of ground station fiducial networks and global gravity field models. Early SLR brought the results of orbit determination and station positions to the meter level of accuracy. The SLR network was expanded in the 1970s and 1980s as other groups built and deployed systems, and technological improvements began the evolution toward the decimeter and centimeter accuracy. Since 1976, the main geodetic target has been LAGEOS (subsequently joined by LAGEOS-2 in 1992), providing the backbone of the SLR technique's contribution to the realization of the International Terrestrial Reference Frame (ITRF). Lunar tracking activity began in 1969 after the deployment of the first retro-reflector array on the surface of the Moon by the Apollo 11 astronauts.

Tracking campaigns were initially organized through COSPAR and through the Satellite and Lunar Laser Ranging (SLR/LLR) Sub-commission on the Coordination of Space Techniques for Geodesy and Geodynamics (CSTG). With strong encouragement from the President of the CSTG, the Sub-commission Steering Committee undertook the formation of the International Laser Ranging Service, ILRS in April 1998, following a similar initiative that had brought the GPS community together under the International GPS (now GNSS) Service, IGS, in 1993. The ILRS is one of the space geodetic services of the International Association of Geodesy (IAG) and is a member of the IAG's Global Geodetic Observing System (GGOS).

The ILRS is a major component of GGOS, providing observations that contribute to the determination of the three fundamental geodetic observables and their variations, that is, Earth's shape, Earth's gravity field and Earth's rotational motion. The ILRS continues as one of the fundamental inputs to the ITRF. Currently, 40 stations in the ILRS network track over 100 satellites in LEO, MEO, GNSS, and synchronous orbits. Some stations in the ILRS network support lunar ranging, with plans to extend ranging to interplanetary missions with optical transponders.

On the current path toward mm accuracy SLR and LLR practitioners are now building new systems and upgrading old ones to improve ground system performance using higher pulse repetition rates (0.1 – 100 kHz) for faster data acquisition; smaller, faster slewing telescopes for more rapid target acquisition and pass interleaving; capabilities to ranging from Low Earth Orbiting (LEO) satellites to the Earth navigation satellites; more accurate pointing for greater link efficiency; narrower laser pulse widths for greater precision; new detection systems for greater ranging accuracy; greater temporal, spatial, and spectral filtering for improved signal to noise conditions; more automation for operational economy (24/7) and greater temporal coverage; and modular construction and more off-the-shelf components for lower fabrication/operations/ maintenance cost.

Over the next 5 years, considerable expansion to the ILRS network is anticipated (see Table 1). However significant geographic gaps will exist in Africa, Latin America, Oceana, and Antarctica.

Table. Future ILRS Network Developments

Site Name	Type	Agency	Timeframe
La Plata, Argentina	Upgraded core site	BKG, Germany	2020 – 2021
San Juan, Argentina	Upgraded SLR system	NAOC, China	2020 – 2021
Metsähovi, Finland	New SLR system	FGI, Finland	2020 – 2021
Greenbelt, MD, USA	Replacement core site	NASA, USA	2022 – 2024
Haleakala, HI, USA	Replacement core site	NASA, USA	2024 – 2026
McDonald, TX, USA	Replacement core site	NASA, USA	2022 – 2025
Ny Ålesund, Norway	New core site	NMA, Norway/NASA, USA	2022 – 2025
Ensenada, Mexico	New SLR site	IPIE, Russian Federation	2022 – 2026
Java, Indonesia	New SLR site	IPIE, Russian Federation	2022 – 2026
Gran Canaria, Spain	New SLR in core site	IPIE, Russian Federation	2022 – 2026
Tahiti, French Polynesia	New SLR system	IPIE, Russian Federation	2022 – 2026
Mt Abu, India	New SLR site	ISRO, India	2020 – 2022
Ponmundi, India	New SLR site	ISRO, India	2020 – 2022
Tsukuba, Japan	New SLR site	JAXA, Japan	2022 – 2024
Yebes, Spain	New SLR site	IGS, Spain	2022 – 2024

Mission

The ILRS collects, merges, analyzes, archives and distributes Satellite Laser Ranging (SLR) and Lunar Laser Ranging (LLR) observation data sets of sufficient accuracy to satisfy the GGOS objectives of a wide range of scientific, engineering, and operational applications and experimentation. The basic observable is the precise time- of-flight of an ultra-short laser pulse to and from a retroreflector-equipped satellite. These data sets are used by the ILRS to generate a number of fundamental added value products, including but not limited to:

- Centimeter accuracy satellite ephemerides;
- Earth orientation parameters (polar motion and length of day);
- Three-dimensional coordinates and velocities of the ILRS tracking stations;
- Time-varying geocenter coordinates;
- Static and time-varying coefficients of Earth's gravity field;
- Fundamental physical constants;
- Lunar ephemerides and librations;
- Lunar orientation parameters.

Structure

The ILRS structure includes the following permanent components:

- Tracking Station Network;
- Operations Centers;
- Global Data Centers;
- Analysis, Lunar Analysis, Associate Analysis, and Combination Centers;
- Central Bureau;
- Governing Board
- Specialized Standing Committees (Analysis, Missions, Networks and Engineering, Data Formats and Procedures, and Transponders).

Information on these permanent components can be found in the ILRS website (http://ilrs.gsfc.nasa.gov/). From time to time, the ILRS also establishes temporary Study Groups to address timely topics.

Governing Board (2019-2020)

- *Michael Pearlman*, Ex-officio, Director Central Bureau
- *Carey Noll*, Ex-officio, Secretary Central Bureau
- *Urs Hugentobler*, Ex-officio, Repr. IAG Commission 1
- *Daniela Thaller*, Appointed, IERS Repr. to ILRS
- *Giuseppe Bianco*, Appointed, EUROLAS Network Repr.
- *Georg Kirchner*, Appointed, EUROLAS Network Repr.
- *James Bennett*, Appointed, WPLTN Network Repr.
- *Zhang Zhongping*, Appointed, WPLTN Network Repr.
- *Jan McGarry*, Appointed, NASA Network Repr.
- *Stephen Merkowitz*, Appointed, NASA Network Repr.
- *Vincenza Luceri*, Elected, Analysis Center Repr.
- *Erricos Pavlis*, Elected, Analysis Center Representative
- *Christian Schwatke*, Elected, Data Center Repr.
- *Jean-Marie Torre*, Elected, LLR Representative
- *Toshimichi Otsubo*, Elected, At Large Repr. (Chair)
- *Matthew Wilkinson*, Elected, At Large Representative
- *Ulrich Schreiber*, Board Appointed Member
- *Krzysztof Sośnica*, Board Appointed Member

Past chairs of the ILRS Governing Board

- John Degnan
- Werner Gurtner (deceased)
- Graham Appleby
- Giuseppe Bianco

Products

The most important aspects of the SLR and LLR observations are absolute accuracy and long, stable time histories at a number of sites. Accuracy approaches the level of a few mm for modern stations; time histories can be 40 years or more on some satellites (e.g., LAGEOS, Starlette, Beacon), and now more than 50 years on the Moon. Since the inception of the service, the ILRS has put the generation of official analysis products high on its agenda. Official submissions to the IERS include weekly solutions for station coordinates and Earth Orientation Parameters (EOPs) submitted on a daily frequency. Additionally, some of the ILRS Analysis Centers (ACs) submit estimates of GM and time-varying geocenter motion to the IERS Global Geophysical Fluids Center. Other user products include static and time-varying coefficients of Earth's gravity field, accurate satellite ephemerides for POD and validation of altimetry, relativity, and satellite dynamics, backup POD for other missions, and Lunar ephemeris for relativity studies and lunar libration for lunar interior studies.

The products of the Analysis, Lunar Analysis, and Associate Analysis Centers are made available to the scientific community through the two Global Data Centers:

- Crustal Dynamics Data Information System (CDDIS) at NASA’s Goddard Space Flight Center, Greenbelt, MD, USA
- European Data Center (EDC), at DGFI - TUM, Munich, Germany

The high accuracy of SLR/LLR data products support many scientific, engineering, and operational applications including:

- Realization and maintenance of the International Terrestrial Reference Frame (ITRF)
- Access to Earth’s center of mass relative to the global network and its time variations
- Monitoring three-dimensional deformations of the solid Earth
- Monitoring Earth rotation variations and polar motion
- Monitoring the long wavelength static and dynamic components of Earth's gravity field.
- Supporting, via precise ranging to altimeter satellites, the monitoring of variations in the topography of the liquid and solid Earth (ocean circulation, mean sea level, ice sheet thickness, wave heights, vegetation canopies, etc.)
- Calibration and validation of microwave tracking techniques (e.g., GPS, GLONASS, Galileo, BeiDou, and DORIS)
- Picosecond global time transfer experiments
- Determination of non-conservative forces acting on satellites
- Determination of satellite attitude
- Astrodynamical observations including determination of the dynamic equinox, obliquity of the ecliptic, and the precession constant
- Gravitational and general relativistic tests, including Einstein's Frame-dragging, Equivalence Principle, the Robertson-Walker b parameter, and time rate of change of the gravitational constant, G
- Lunar physics including the dissipation of rotational energy, shape of the core-mantle boundary (Love Number k2), and free librations and stimulating mechanisms
- Solar System ties to the International Celestial Reference Frame (ICRF)
- Tracking of space debris

Contacts

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Toshi Otsubo, Chair, ILRS Governing Board
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Erricos Pavlis, ILRS Analysis Coordinator
epavlis@umbc.edu

Publications

The ILRS Central Bureau maintains a comprehensive website as the primary vehicle for the distribution of information within the ILRS community. This site can be accessed at http://ilrs.gsfc.nasa.gov. Many ILRS and related publications and reports can now be accessed online through the ILRS website including:

- ILRS Terms of Reference and
- ILRS Standing Committee charters, members, reports
- ILRS network description and status
- ILRS satellite descriptions and tracking information
- ILRS workshop/meeting reports and presentations
- ILRS service reports
- ILRS associates directory
- ILRS organization and technical contacts
- Science and engineering references and reports

International VLBI Service for Geodesy and Astrometry (IVS)

Chair of Directing Board: **Axel Nothnagel** (Austria)
Coordinating Center Director: **Dirk Behrend** (USA)

https://ivscc.gsfc.nasa.gov

Development

The International VLBI Service for Geodesy and Astrometry (IVS) is an international collaboration of organizations, which operate or support Very Long Baseline Interferometry (VLBI) components. IVS was established in 1999 and became a service of IAG that year. In 2000, IVS was recognized as a service of the International Astronomical Union (IAU). In 2013 an agreement was signed between the IVS and the International Science Council (ISC; formerly ICSU) accepting the service as a Network Member of ISC's World Data System (WDS). The IVS interacts closely with the International Earth Rotation and Reference Systems Service (IERS), which is tasked by IAU and IUGG/IAG with maintaining the international celestial and terrestrial reference frames (ICRF and ITRF).

Mission/Objectives

The objectives of IVS are:

- To provide a service to support geodetic, geophysical, and astrometric research and operational activities.
- To promote research and development activities in all aspects of the geodetic and astrometric VLBI technique.
- To interact with the community of users of VLBI products and to integrate VLBI into a global Earth observing system.

To meet these objectives, IVS coordinates VLBI observing programs, sets performance standards for VLBI stations, establishes conventions for VLBI data formats and data products, issues recommendations for VLBI data analysis software, sets standards for VLBI analysis documentation, and institutes appropriate VLBI product delivery methods to ensure suitable product quality and timeliness. IVS closely coordinates its activities with the astronomical community because of the dual use of many VLBI facilities and technologies for both astronomy and astrometry/geodesy.

Products

VLBI data products currently available are

- All components of Earth orientation
- Terrestrial reference frame
- Celestial reference frame
- Tropospheric parameters
- Baseline lengths

All VLBI data products are archived in IVS Data Centers and are publicly available.

Structure / Board / Members

IVS accomplishes its goals through Permanent Components. As of 2020 the IVS has:

- 34 Network Stations, acquiring high performance VLBI data.
- 3 Operation Centers, coordinating activities of Network Stations.
- 8 Correlators, processing acquired data, providing feedback to stations and providing processed data to analysts.
- 5 Data Centers, distributing products to users, providing storage and archiving functions.
- 29 Analysis Centers, analyzing the data and producing results and products.
- 7 Technology Development Centers, developing new VLBI technology.
- 1 Office for Outreach and Communications, promoting knowledge of the VLBI technique and IVS activities.
- 1 Coordinating Center, coordinating daily and long-term activities of IVS.

All together there are 88 Permanent Components, representing 42 organizations in 21 countries, and ~315 individuals who are Associate Members. The 42 organizations that support IVS components are IVS Member Organizations. There are also 6 Affiliated Organizations that cooperate with IVS on issues of common interest but do not support an IVS component.

In addition, the IVS has a Directing Board to determine policies, standards, and goals. The current IVS Directing Board consists of the following members (alphabetical):

1. *J. Anderson* (Germany) Analysis and Data Centers Representative
2. *D. Behrend* (USA) Coordinating Center Director
3. *P. Charlot* (France) IAU Representative
4. *F. Colomer* (Spain) Network Stations Representative
5. *A. de Witt* (South Africa) At Large member
6. *J. Gipson* (USA) Analysis Coordinator
7. *R. Haas* (Sweden) IERS representative
8. *D. Hall* (USA) Correlators and Operation Centers Representative
9. *H. Hase* (Argentina) Network Stations Representative
10. *E. Himwich* (USA) Network Coordinator
11. *N. Kotary* (USA) Office for Outreach and Communications
12. *J. Li* (China) Member-at-Large
13. *E. Nosov* (Russia) At Large member
14. *A. Nothnagel* (Austria) Analysis and Data Centers Representative
15. *C. Ruszczyk* (USA) Technology Development Centers Representative
16. *O. Titov* (Australia) IAG Representative
17. *G. Tuccari* (Italy) Technology Coordinator

The Office for Outreach and Communications was created in 2019 to establish and maintain an outreach program that would promote knowledge of the VLBI technique and the activities of the IVS and foster an understanding of the importance of its products for the scientific communities and the general public. The outreach Web pages are being established under the URL https://vlbi.org, and fledgling Twitter and Instagram accounts have been created. A new IVS logo was designed, replacing the 20-year-old logo.

Committees and Working Groups

IVS currently has one active working group, one task force, and three committees:

- Working Group 7 on Satellite Observations with VLBI.
- Task Force on Seamless Auxiliary Data.
- Observing Program Committee (OPC).
- Committee on Training and Education (CTE).
- VGOS Technical Committee (VTC).

Publications and Meetings

IVS publishes a Biennial Report, a thrice-annual Newsletter, and Proceedings from its biennial General Meeting. All publications are published electronically on the Web site. IVS holds a General Meeting every two years, a Technical Operations Workshop every two years, and an Analysis Workshop every year. Information about all IVS activities is available at the IVS Web site under the URLs https://vlbi.org and https://ivscc.gsfc.nasa.gov.

International Gravity Field Service (IGFS)

Chair: **R. Barzaghi**,
Politecnico di Milano, Italy
riccardo.barzaghi@polimi.it
Director of Central Bureau: **G. Vergos**
Aristotle University of Thessaloniki, Greece
vergos@topo.auth.gr

http://igfs.topo.auth.gr/

Objectives

IGFS is a unified "umbrella" IAG service, which will:

- Coordinate collection, validation, archiving and dissemination of gravity field related data
- Coordinate courses, information materials and general public outreach relating to the Earth's gravity field
- Unify gravity products for the needs of GGOS, the Global Geodetic Observing System

The IGFS coordinates the following "Level-1" IAG services:

- BGI (Bureau Gravimetrique International), Toulouse, France
- ISG (International Service for the Geoid), Politecnico di Milano, Milano, Italy
- IGETS (International Geodynamics and Earth Tides Service), EOST, Strasbourg, France
- ICGEM (International Center for Global Earth Models), GFZ, Potsdam, Germany
- IDEMS (International Digital Elevation Model Service), ESRI, Redlands, CA, USA

Furthermore, IGFS has one Product Center, namely COST-G (Combination Service for Time-variable Gravity fields) at AIUB, Berne, Switzerland.

The overall goal of IGFS is to coordinate the servicing of the geodetic and geophysical community with gravity field related data, software and information. The combined data of the IGFS entities will include global geopotential models, terrestrial, airborne, satellite and marine gravity observations, Earth tide data, GPS/leveling data, digital models of terrain and bathymetry, as well as ocean gravity field and geoid from satellite altimetry. Both the static and the temporal variations of the gravity field will be covered by the IGFS.

IGFS will – in cooperation with the Services - make a special effort in trying to secure release of data from national and international institutions holding data on the spatial and temporal gravity variations, geoid and the surface heights of the Earth, to make them widely available to the scientific community.

IGFS will coordinate regional conferences, tutorials and schools to train young scientists and members of national institutions in the various aspects of the gravity field science, computations, and data collection. IGFS will maintain a publication activity related to the gravity field, especially through "Newton's Bulletin".

Structure

The Service is organized by means of the following structure:

- Advisory Board
- Central Bureau
- Product Centers
- Services

The Advisory Board is composed of:

- Directors (or their delegates) of each of the Services/Centers of IGFS
- Chairs of the IGFS working groups
- Presidents (or their delegates) of the IAG Commissions related to the Service work
- A representative of the IAG Executive Committee (IAG- EC)
- Members appointed among the IAG affiliates.

The Advisory Board:

- Coordinates the scientific strategy
- Coordinates the joint activity of the Centers
- Oversees the participation of the Service in international projects
- Presents to the IAG-EC proposals for associating new centers

- Elects the IGFS affiliates upon nomination by the Services/Centers or affiliates.

The Advisory Board is appointed for four years between IUGG General Assemblies. The existing Advisory Board selects new members as required and nominates the Chair of the IGFS. The election is to be confirmed by the IAG-EC. The Advisory Board makes decisions by majority vote; it can also vote by email. The Advisory Board decides the Terms of Reference for IGFS.

IGFS Services and Centers

The IGFS Services and Centers are the "operating arms" of IGFS. They are committed to produce services and products related to the gravity field of the Earth and/or the planets and are approved by the IAG-EC. Services and Centers can include bodies of structures external to the IAG (e.g., the BGI which is reporting to FAGS). They will have their own governing bodies, nominated according to internal rules, also taking into account the interests of the supporting entities. In particular, each governing body will have a Director, elected according to internal rules.

Services and Centers will maintain a list of data and products, providing them to the general public according to their policy of dissemination. They will deliver services in the form of data archiving, data analysis and dissemination, software, training on gravity field estimation, support to field campaigns etc. COST-G, the IGFS Product Center, will provide consolidated monthly global gravity field models in terms of spherical harmonic coefficients and derived grids by combining solutions from individual Analysis Centers. The activities of each Service/Center will be reviewed annually by the IAG-EC.

IGFS Central Bureau

The IGFS Central Bureau will act as the central coordination and communication center of the IGFS. The Central Bureau will provide: a link between the IGFS entities, IAG, and external projects, networks or organizations (oceanic, atmospheric, hydrologic…); a link to the GGOS Bureaus in order to communicate their requirements and recommendations to the IGFS Services. It will also implement standards and recommendations related to gravity field observations, secure consistency with geometric standards and promote their use within the geoscience community. Furthermore, the Central Bureau will maintain the IGFS website and arrange gravity field related meetings and workshops.

Working groups

JWG GGOS 0.1.3: Implementation of the International Height Reference Frame (IHRF) (joint with GGOS, Commission 1, Commission 2, ICCT)

JWG GGOS: Towards a consistent set of parameters for the definition of a new GRS (joint with GGOS, Commissions 1, Commission 2, ICCT, IERS Committee on EGV)

JSG T26: Geoid/quasi-geoid modelling for the realization of the geopotential height datum (joint with Commission 2, GGOS, ICCT)

JSG T.37: Theory and methods related to the combination of high-resolution topographic/bathymetric models in geodesy (joint with ICCT, IDEMS)

IGFS Advisory Board

- *H. Abd-Elmotaal* (Egypt)
- *J.-P. Barriot* (French Polynesia)
- *S. Bonvalot* (France)
- *S. Bettadpur* (USA)
- *R. Forsberg* (Denmark)
- *Y. Fukuda* (Japan)
- *T. Gruber* (Germany)
- *J. Huang* (Canada)
- *E. S. Ince* (Germany)
- *A. Jäggi* (Switzerland)
- *K. Kelly* (USA)
- *U. Marti* (Switzerland)
- *T. Otsubo* (Japan)
- *R. Pail* (Germany)
- *M. Reguzzoni* (Italy)
- *M. G. Sideris* (Canada)
- *L. Sanchez* (Germany/Columbia)
- *I. N. Tziavos* (Greece)
- *L. Vitushkin* (Russia)
- *Y. Wang* (USA)
- *H. Wziontek* (Germany)

International Centre for Global Earth Models (ICGEM)

Director: **E. Sinem Ince** (Germany)

http://icgem.gfz-potsdam.de

Terms of Reference

The determination of Earth's global gravity field is one of the main tasks of geodesy: it serves as a reference for geodesy itself and provides essential information about the Earth, its interior and its fluid envelope for all geosciences. Thus, it is important to model the gravity field globally and make the state-of-the-art models available to public as geodetic products. With accurate satellite measurements, it is now possible to map the static gravity field as well as its variations with much higher spatial and temporal resolutions compared to the first of its kinds. The list of such models is continuously growing and requires dedicated maintenance.

International Centre for Global Earth Models (ICGEM) is one of the five services coordinated by the International Gravity Field Service (IGFS) of the International Association of Geodesy (IAG). The primary objective of the ICGEM service is to collect and archive all existing static and temporal global gravity field models and provide an online interactive calculation service for the computation of gravity field functionals freely available to the general public. The calculation of the different functionals of the geopotential (e.g. geoid, gravity anomaly, gravity disturbance, equivalent water height) from a defined global model, on a specified grid or points with respect to a defined reference system, is not trivial for science and scientists and is a responsibility of geodesy too. Additionally, it is important to visualize the spatial and temporal distribution of the global gravity field and therefore interactive visualization is also provided by ICGEM.

Development

With the initiation of IGFS and the commitment for hosting and financial support by German Research Centre for Geosciences (GFZ), the ICGEM service was established in 2003 and aimed to collect and archive static gravity field models initially. Due to the increasing interest of the users and model developers, temporal gravity field models have also been made available on the same platform after the launch of GRACE mission. The service has been extensively used and promises further developments to serve multidisciplinary research.

Objectives

ICGEM is designed as a web-based service and comprehends:

- collecting and long-term archiving of existing static global gravity field models, solutions from dedicated shorter time periods (e.g. monthly GRACE/GRACE-FO models), and topographic gravity field models,
- making the above-mentioned models available on the web in a standardized format as described in Barthelmes and Förste (2011),
- since late 2015, the possibility of assigning Digital Object Identifiers (DOIs) to the models,
- a web interface to calculate gravity field functionals from the spherical harmonic models on freely selectable grids and user-defined points,
- a 3-D interactive visualization of the models (geoid undulations and gravity anomalies),
- quality checks of the static gravity field models via comparisons with other models in the spectral domain and w.r.t. GNSS/levelling-derived geoid undulations,
- the visualization of surface spherical harmonics as tutorial,
- the theory and formulas of the calculation service documented in GFZ's Scientific Technical Report STR09/02 (Barthelmes, 2013),
- manuals and tutorials for global gravity field modelling and usage of the service (Barthelmes, 2014) and

scientific journal papers for educational and reference purposes (Ince et al. 2019) and finally,
- the ICGEM web-based gravity field discussion forum for questions on ICGEM and its products and to request knowledge exchange.

Services

The Models

ICGEM relies on other centres and institutes who develop static and temporal gravity field models that are made available on ICGEM. By February 2020, 176 static gravity field models are listed in ICGEM (http://icgem.gfz-potsdam.de/tom_longtime). Apart from 17 older models, all other models are available in the form of spherical harmonic coefficients. Models from dedicated time periods (e.g. monthly solutions from GRACE) of Science Data System Centres CSR, JPL, and GFZ, and various other solutions such as from CNES/GRGS and ITSG are also available. Recently, the combined monthly models produced based on the COST-G standards have been made available (http://icgem.gfz-potsdam.de/series). Finally, topographic gravity field models have been made available for the first time in 2014 as requested by users and model developers (http://icgem.gfz-potsdam.de/tom_reltopo). Such models can enhance the benefit from the gravity field products in high frequency components and in multidisciplinary studies.

Digital Object Identifiers (DOI)

In order to support open science and open data, ICGEM does not only provide free access to the models but supports the assignment of Digital Object Identifiers (DOI) to make the models citable. Since 2016, ICGEM together with the GFZ Library and Information Services, provides a service to assign a DOI to the models, i.e. to the datasets of the coefficients. Currently, over 30 models have been assigned DOIs. ICGEM encourages the model developers to request DOI at http://pmd.gfz-potsdam.de/panmetaworks/metaedit.

The 3D Visualization

An online interactive service for the visualization of the models (in terms of height anomalies and gravity anomalies) as illuminated projection on a freely rotatable sphere is available (http://icgem.gfz-potsdam.de/vis3d/longtime, see also Fig. 1). Differences of two models, arbitrary degree windows, zooming in and out, are possible. The visualization of spherical harmonics is also possible for tutorial purposes (see Fig. 2).

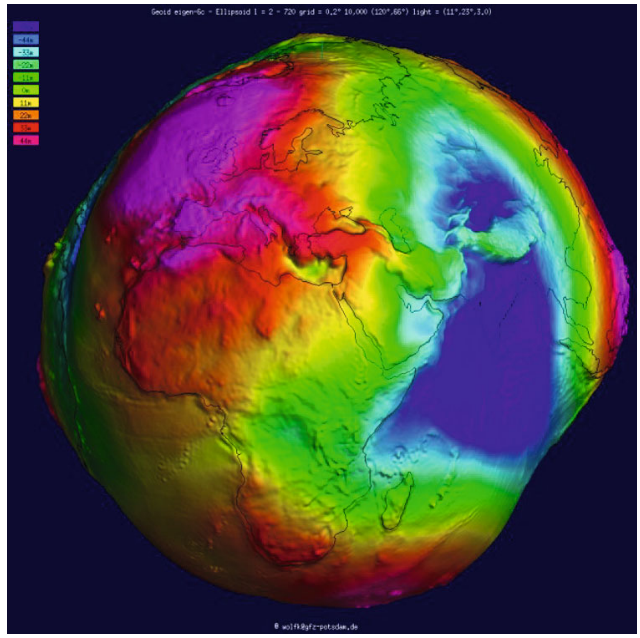

Fig. 1 Visualization (geoid) of a global gravity field model.

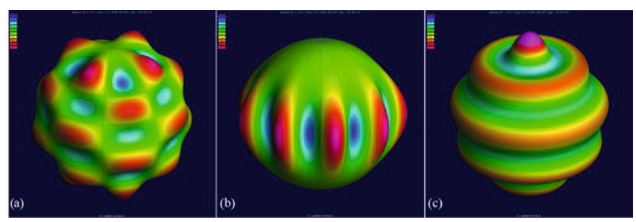

Fig. 2 3D visualization of spherical harmonics as a tutorial. The images show (a) tesseral (l = 9, m = 4), (b) sectorial (l = 9, m = 9), and (c) zonal (l = 9, m = 0) spherical harmonics (Ince et al. 2019).

The Calculation Service

A web-interface to calculate gravity field functionals from the spherical harmonic models on freely selectable grids or at user-defined points with respect to a reference system of the user's choice is provided. The following functionals are available in the grid calculation (http://icgem.gfz-potsdam.de/calcgrid):

- pseudo height anomaly on the ellipsoid (or at arbitrary height above the ellipsoid)
- height anomaly (on the Earth's surface)
- geoid height (height anomaly plus spherical shell approximation of the topography)
- gravity disturbance

- gravity disturbance in spherical approximation (at arbitrary height above the ellipsoid)
- gravity anomaly (classical and modern definition)
- gravity anomaly (in spherical approximation, at arbitrary height above the ellipsoid)
- simple Bouguer gravity anomaly
- gravity at the Earth's surface (including the centrifugal acceleration)
- gravity on the ellipsoid (or at arbitrary height above the ellipsoid, including the centrifugal acceleration)
- gravitation on the ellipsoid (or at arbitrary height above the ellipsoid, without centrifugal acceleration)
- second derivative in spherical radius direction (at arbitrary height above the ellipsoid)
- equivalent water height (water column)

Beside the functionals listed above, deflections of vertical can be computed at user-defined points (http://icgem.gfz-potsdam.de/calcpoints).

In the calculation setting, filtering is possible by selecting the range of used coefficients or the filter length of a Gaussian averaging filter. The calculated grids together with the calculation settings included in the header part can be downloaded once the calculation is completed. For grid calculations, the corresponding plots created using GMT (in Postscript or Portable Network Graphics format) are available for download (see Fig. 3). Since 2018, calculations on user-defined points are available (see Fig. 4) and the results can be downloaded in ASCII format as well.

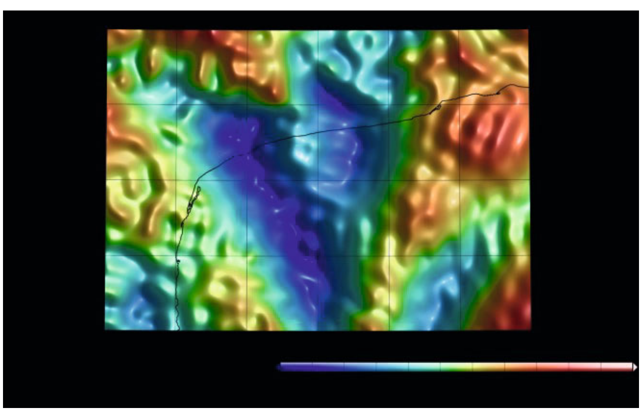

Fig. 3 Example of grid and plot generation by the calculation service: gravity disturbances of the Chicxulub crater region from the model XGM2019e_2159.

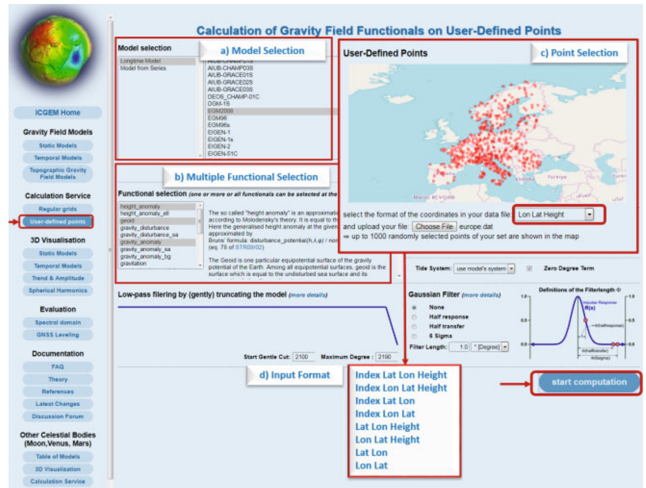

Fig. 4 User-defined point calculation interface and settings (Ince et al. 2019)

The table is interactively re-sortable for all columns by clicking in the header cells.

Nr	Model	Nmax	Australia (201 points)	Brazil (1112 points)	Canada (2691 points)	Europe (1047 points)	Japan (816 points)	USA (6169 points)	All (12036 points)
176	**XGM2019**	760	0.217 m	0.44 m	0.151 m	0.14 m	0.125 m	0.264 m	0.2494 m
176	**XGM2019e_2159**	2,190	0.215 m	0.438 m	0.128 m	0.127 m	0.09 m	0.248 m	0.2361 m
175	**GO_CONS_GCF_2_TIM_R6e**	300	0.318 m	0.502 m	0.29 m	0.34 m	0.431 m	0.396 m	0.3832 m
174	**ITSG-Grace2018s**	200	0.404 m	0.545 m	0.387 m	0.504 m	0.573 m	0.496 m	0.4837 m
173	**EIGEN-GRGS.RL04.MEAN-FIELD**	300	0.327 m	0.507 m	0.298 m	0.345 m	0.447 m	0.404 m	0.391 m
172	**GOCO06s**	300	0.318 m	0.503 m	0.292 m	0.341 m	0.43 m	0.398 m	0.3847 m
171	**GO_CONS_GCF_2_TIM_R6**	300	0.317 m	0.501 m	0.29 m	0.34 m	0.431 m	0.396 m	0.383 m
170	**GO_CONS_GCF_2_DIR_R6**	300	0.313 m	0.503 m	0.292 m	0.339 m	0.432 m	0.396 m	0.3838 m
169	**IGGT_R1C**	240	0.388 m	0.529 m	0.427 m	0.457 m	0.574 m	0.464 m	0.4689 m
168	**Tongji-Grace02k**	180	0.432 m	0.592 m	0.475 m	0.587 m	0.661 m	0.525 m	0.5357 m
167	**SGG-UGM-1**	2,159	0.217 m	0.446 m	0.13 m	0.121 m	0.076 m	0.245 m	0.2353 m
166	**GOSG01S**	220	0.359 m	0.518 m	0.373 m	0.426 m	0.526 m	0.442 m	0.4392 m
165	**IGGT_R1**	240	0.317 m	0.513 m	0.348 m	0.387 m	0.483 m	0.412 m	0.4111 m
164	**IfE_GOCE05s**	250	0.337 m	0.512 m	0.329 m	0.385 m	0.48 m	0.414 m	0.4081 m
163	**GO_CONS_GCF_2_SPW_R5**	330	0.33 m	0.511 m	0.299 m	0.346 m	0.442 m	0.396 m	0.3873 m
162	**GAO2012**	360	0.293 m	0.531 m	0.309 m	0.453 m	0.759 m	0.366 m	0.4177 m
161	**XGM2016**	719	0.218 m	0.44 m	0.151 m	0.14 m	0.125 m	0.263 m	0.2489 m
160	**Tongji-Grace02s**	180	0.452 m	0.605 m	0.478 m	0.596 m	0.669 m	0.53 m	0.5417 m
159	**NULP-02s**	250	0.351 m	0.512 m	0.375 m	0.413 m	0.508 m	0.427 m	0.4284 m
158	**HUST-Grace2016s**	160	0.489 m	0.658 m	0.594 m	0.69 m	0.837 m	0.596 m	0.6273 m

Fig. 5 Comparison of the models w.r.t. GNSS-levelling: Root mean square (rms) about mean of GNSS / levelling minus gravity field model derived geoid heights [m]. Note the XGM2019 is evaluated for two different $N_{\max}$.

ICGEM continues to evaluate the static gravity field models w.r.t. GNSS/levelling derived geoid undulations (see the list in Fig. 5) and in the spectral domain w.r.t. already reliable models (see Figs. 6). Visualization of the improvement of the satellite-only models w.r.t. EIGEN-6C4 over the years are shown as a function of spatial resolution in Fig. 7.Apart from the gravity field models of the Earth, ICGEM hosts similar models for other celestial bodies (Moon, Mars, Venus and Ceres). A 3D visualization of the Moon's geoid is shown in Fig. 8

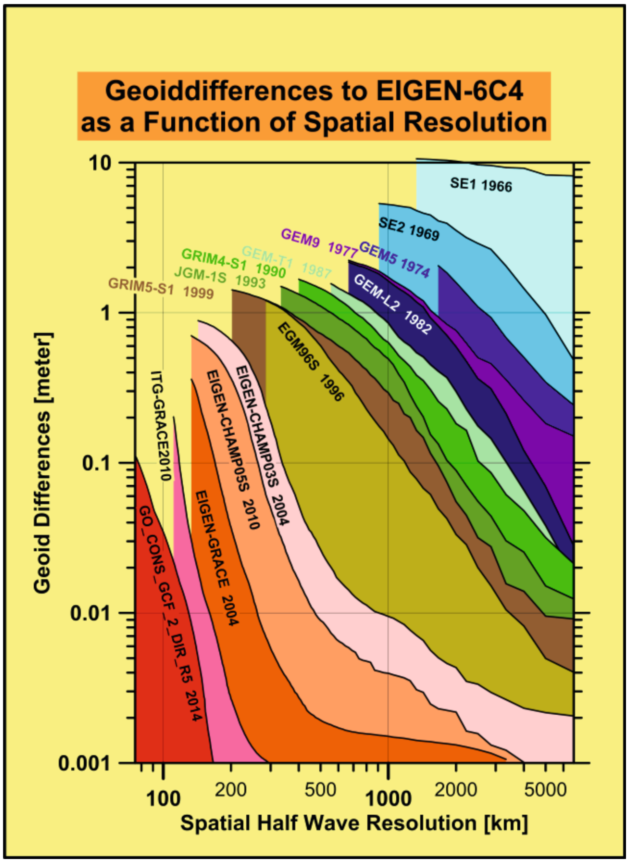

Fig. 6 Comparison of the satellite-only model GO_CONS_GCF_2_DIR_R6 in the spectral domain with one of the most recent models that combines satellite and terrestrial data (EIGEN-6C4).

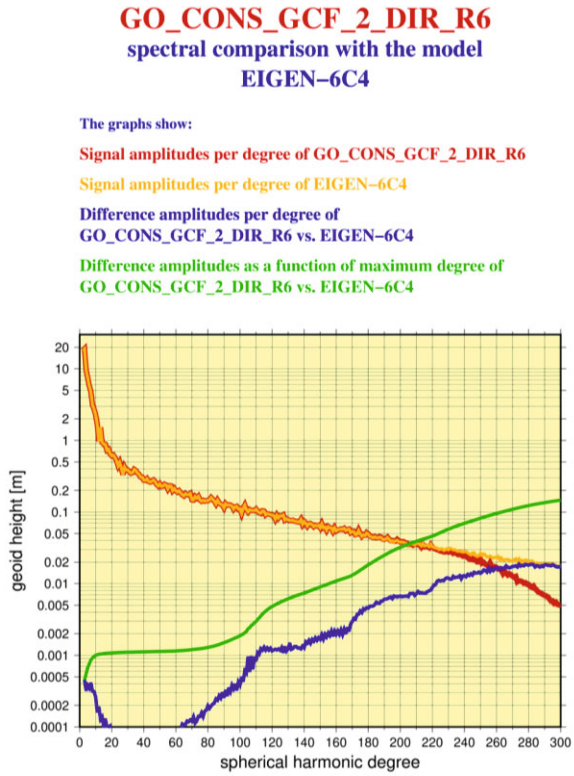

Fig. 7 Visualization of the improvement of satellite-only models over the past decades: Geoid differences to the model EIGEN-6C4 as a function of spatial resolution.

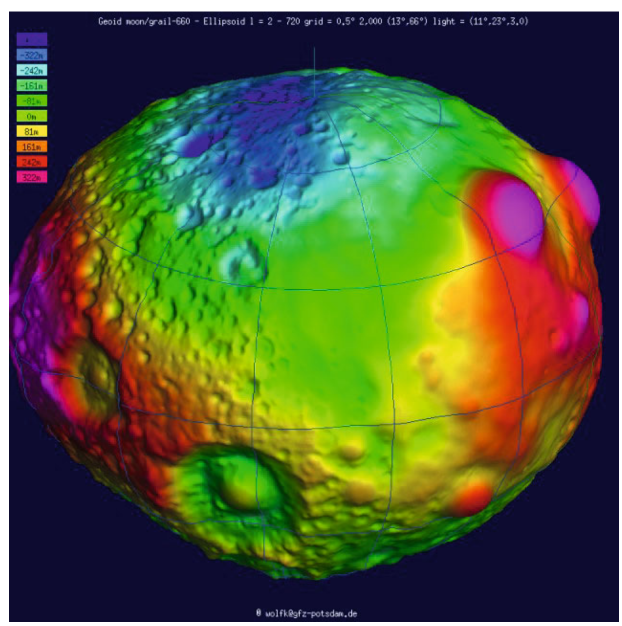

Fig. 8 Visualization of the “Geoid” of the Moon.

FAQs and Discussion Forum

In May 2017, to support the users from different disciplines and levels, ICGEM introduced the Frequently Asked Questions (FAQs) and their short and detailed answers. Such answers are expected not only to help students and researchers for educational purposes, but also to understand the background of the ICGEM products. Moreover, to increase the knowledge exchange with and among the users ICGEM’s discussion forum is expanded and it is encouraged to be used to share gravity field related questions and information.

Outlook

ICGEM is a unique platform to collect and provide access to a comprehensive list of gravity field models that are of static, temporal and topographic kind. Beside the calculation and visualization services, complementary documentations about the models are made available. The ICGEM service is a worldwide service and is not aimed to a specific user community. It continues to update its content with new models and additional features as requested by users, and depending on availability. The coordination and communication of the ICGEM Service are made through the ICGEM's staff (icgem@gfz-potsdam.de) with input from international contributors.

Data Policy

Access to global gravity field models, derived products and tutorials, once offered by the center, shall be unrestricted for any external user.

Reference

Reference for ICGEM Service and its products is as follows:

Ince, E. S., Barthelmes, F., Reißland, S., Elger, K., Förste, C., Flechtner, F., and Schuh, H.: ICGEM – 15 years of successful collection and distribution of global gravitational models, associated services, and future plans, Earth Syst. Sci. Data, 11, 647–674, https://doi.org/10.5194/essd-11-647-2019, 2019.

Other references:

Barthelmes, F.: Definition of Functionals of the Geopotential and Their Calculation from Spherical Harmonic Models: Theory and formulas used by the calculation service of the International Centre for Global Earth Models (ICGEM), Scientific Techni- cal Report STR09/02, Revised Edition, January 2013, Deutsches GeoForschungZentrum GFZ, https://doi.org/10.2312/GFZ.b103-0902-26,2013.

Barthelmes, F.: Global Models, in: Encyclopedia of Geodesy, edited by: Grafarend, E., Springer International Publishing, 1–9, https://doi.org/10.1007/978-3-319-02370-0_43-1, 2014.

Barthelmes, F. and Förste, C: The ICGEM-format. Potsdam: GFZ German Research Centre for Geosciences, available at: http: //icgem.gfz-potsdam.de/ICGEM-Format-2011.pdf (last access: 25 February 2020), 2011.

Staff

ICGEM is hosted by GFZ Potsdam. After the long-time director of the ICGEM service *Franz Barthelmes'* retirement, current staff consists of

E. Sinem Ince

Sven Reißland

The staff is allocated part-time and responds to queries on a best-effort basis.

Point of Contact

E. Sinem Ince
Helmholtz Centre Potsdam
GFZ German Research Centre for Geosciences
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Germany
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International Digital Elevation Model Service (IDEMS)

Director: **Kevin M. Kelly** (USA)

https://idems.maps.arcgis.com/home/

Introduction

The International Digital Elevation Model Service (IDEMS) is one of five Servics of the International Gravity Field Service (IGFS) of the International Association of Geodesy (IAG). IDEMS provides a focus for distribution of data and information about digital elevation models, spherical-harmonic models of Earth’s global topography, lunar and planetary DEM, relevant software and related datasets (including representation of Inland Water within Digital Elevation Models) which are available in the public domain. IDEMS is hosted and operated by Environmental Systems Research Institute (Esri) (http://www.esri.com/).

Products

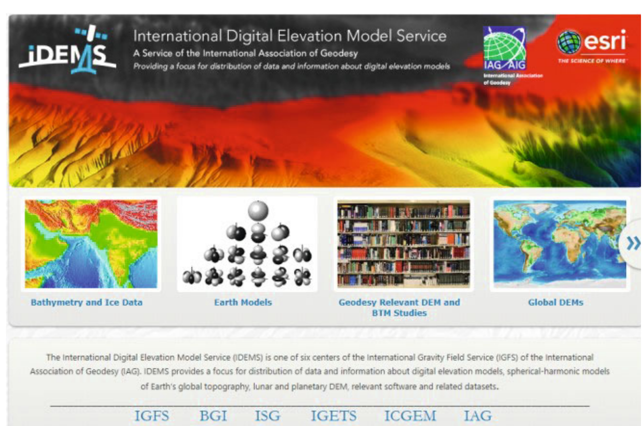
IDEMS currently hosts 31 sources of terrestrial and planetary DEM data providers (see Table 1) and 126 references of DEM and bathymetry research papers relevant to geodesy and Earth sciences. The IDEMS bibliography is updated regularly (currently two times per year) to provide the user community with an up-to-date overview over key developments in DEM production, validation and applications. The IDEMS bibliography includes recent and seminal papers describing relevant data sets of Earth's topography, bathymetry, ice data and composite elevation models. Some DEM sources appear in multiple categories to facilitate source discovery for the researcher. IDEMS serves as a repository of links to DEM data providers rather than a DEM data storage facility. The site also provides access to Esri’s free ArcGIS Earth software which is fully integrated with the ArcGIS platform for accessing, sharing, and publishing maps and data. ArcGIS Earth is available here: (https://www.esri.com/en-us/arcgis/products/arcgis-earth/overview).

Over the last 3 years, the IDEMS website has been continually updated with new DEM datasets, both terrestrial and planetary. Table 1 lists the current content available from the IDEMS website.

Structure

The Governing Board (GB) of IDEMS consists of five members who oversee the operation and general activities of the service. The GB is structured as follows:

Director of IDEMS:	Mr *Kevin M Kelly*
Deputy Director of IDEMS:	Dr *Fei Wang*
IAG/IGFS representative:	Dr *Riccardo Barzhagi*
Advisory member:	Dr *Christian Hirt*
Advisory member:	Dr *Michael Kuhn*



Screenshot of home page of IDEMS

Table 1. DEM and Related Data Sources Hosted on IDEMS

Bathymetry and Ice Data (12)	Antarctica CryoSat-2 DEM
	Bedmap2
	BOEM Northern Gulf of Mexico Bathymetry
	Elevation Coverage Map (Esri)
	Flight MH370 Bathymetry
	Global Bathymetry BTM (Esri)
	Global Water Body Map (G3WBM)
	Ice, Cloud, and Land Elevation (ICESat / GLAS Data)
	Polar Geospatial Center
	Randolph Glacier Inventory (RGI 6.0)
	SRTM30_PLUS (30 arc-sec grid), 2014
	Svalbard time-lapse terrain data
Global DEMs (14)	ALOS/PRISM AW3D30
	ASTER GDEM v2
	Elevation Coverage Map (Esri)
	Esri Elevation Layers
	ETOPO1 (60 arc-sec grid), 2009
	Global Terrain DEM (Esri)
	Global Water Body Map (G3WBM)
	MERIT DEM (SRTM-based Bare-Earth model), 2017
	NASADEM (reprocessed SRTM model), 2017
	SRTM v3 (NASA)
	SRTM v4.1 (CGIAR-CSI)
	SRTM30_PLUS (30 arc-sec grid), 2014
	TanDEM-X DEM
	Viewfinder Panorama DEMs (2014)
Regional DEMs (7)	Antarctica CryoSat-2 DEM
	Arctic DEM Explorer
	OpenTopography
	Elevation Coverage Map (Esri)
	Esri Elevation Layers
	Polar Geospatial Center
	Svalbard Time-Lapse Terrain Model
Planetary Terrain Data (3)	NASA Planetary Data System (PDS) Geosciences Node
	Planetary topography data archive
	USGS Astrogeology Science Center
Earth Models (4)	Earth2014 (60 arc-sec), 2014
	ICE-6G GIA Model
	Preliminary Reference Earth Model (PREM)
	Topographic Earth Models (LMU Munich)

International Geodynamics and Earth Tide Service (IGETS)

Chair: **Hartmut Wziontek** (Germany)
Director of the Central Bureau: **Jean-Paul Boy** (France)

http://igets.u-strasbg.fr/

1 Terms of Reference

1.1 Objectives

The primary objective of the International Geodynamics and Earth Tide Service (IGETS) is to provide a Service to monitor temporal variations of the Earth gravity field through long-term records from ground gravimeters, tiltmeters, strainmeters and other geodynamic sensors.

IGETS continues the activities of the Global Geodynamic Project (GGP) to provide support to geodetic and geophysical research activities using superconducting gravimeter (SG) data within the context of an international network. IGETS continues the activities of the International Center for Earth Tides (ICET), in particular, in collecting, archiving and distributing Earth tide records from long series of gravimeters, tiltmeters, strainmeters and other geodynamic sensors.

1.2 Products and Goals

IGETS is the main data center of worldwide high precision SG records; the products hosted at the IGETS data centers are:

- Raw gravity and local pressure records sampled at 1 or 2 seconds, in addition to the same records decimated at 1-minute samples (Level 1 products);
- Gravity and pressure data corrected for instrumental perturbations, ready for tidal analysis. This product is derived from the previous datasets, and is computed by one or several Analysis Centers (Level 2 products).
- Gravity residuals after particular geophysical corrections (including solid Earth tides, polar motion, tidal and non-tidal loading effects). This product is also derived from the previous dataset and is computed by one or several Analysis Centers (Level 3 products).

IGETS strives to provide long-term gravity residuals based on repeated absolute gravity measurements at particular stations accessible through the Absolute Gravity database.

IGETS also acts as the main data center of long-term series recorded from other geodynamic sensors (spring gravimeters, tiltmeters, strainmeters, etc.), including the historical dataset from the ICET databank.

IGETS may conduct comparison, validation and distribution of tidal analysis software or any other software, which can be used to process or correct gravity, tilt or strain long time series.

IGETS may organize symposia and workshops to provide a forum for presentation and discussion of all aspects of IGETS activities.

2 Permanent Components

IGETS accomplishes its objectives through the following permanent components:

- Stations
- Analysis Centers
- Data Centers

2.1 Stations

The IGETS network consists of high quality and stability measurements of gravity, tilts and strain, including superconducting gravimeters. Stations should comply with the performance standards for data quality and reliability, developed since 1997 during the Global Geodynamics Project (GGP), specified by the Directing Board.

2.2 Analysis Centers

The Analysis Centers are committed to produce data products accordingly to the recommendations and specifications defined by IGETS Directing Board, and send their final products to the main Data Center for dissemination to researchers and other users. They may produce any of the IGETS products, or any of the corrections needed to compute them.

The primary Analysis Center is responsible for computing SG corrected data (the Level 2 products). The final SG residuals (the Level 3 products) are computed by the secondary Analysis Center. The institutions currently in charge of these tasks are given in the attachment of the ToR; the attachment is not part of the ToR and can be changed by the Directing Board with two-third majority.

2.3 Data Centers

The IGETS Data Centers are repositories of any data products, including station log files. Their primary objectives are to collect, archive and distribute these data with efficiency and reliability. Data centers may mirror some of the other data centers to increase the accessibility of the IGETS datasets.

The primary Data Center hosts all SG data products (Levels 1, 2 and 3). A secondary Data Center is hosting all other datasets, including the historical products. The institutions currently in charge of these tasks are given in the attachment of the ToR, and can be changed by the Directing Board with a two-thirds majority of voting members.

2.4 Central Bureau

The Central Bureau is the executive arm of the IGETS Directing Board, and is responsible for all operational activities of the Service. The Central Bureau coordinates IGETS activities, facilitates communications, maintains documentations and organizes reports, meetings and workshops.

The Central Bureau operates on a term of four years. One year prior to the end of each term, the IGETS Directing Board formally reviews the performances of the Central Bureau, and may then request the Central Bureau to reconfirm its commitment to serve another four years. If the Central Bureau agrees, it submits a proposal for approval by the Directing Board. If the Central Bureau declines, or if the Directing Board chooses to change the Central Bureau, the Directing Board announces a call for proposal for a new IGETS Central Bureau, to take the responsibility including a six-month transition phase.

The Director of the Central Bureau serves as a member of the Directing Board.

IGETS will accept proposals at any time from scientific individuals, groups or institutions to become a new permanent component of the service (this can be a new station, or an analysis and/or data center). The Directing Board will review such proposals for approval.

3 Directing Board

3.1 Role and responsibilities

The Directing Board sets the objectives, determines policies, adopts standards, and sets the scientific and operational goals for IGETS. The Directing Board exercises general oversight of the activities of IGETS including modifications to the organization that are deemed appropriate and necessary to maintain efficiency and reliability. The Directing Board may determine appropriate actions to ensure the quality of the IGETS products.

3.2 Membership

The Directing Board consists of representatives of the IGETS components, members-at-large, appointed members and ex officio members. Its members are:

Elected Members (5)

- Raw Data Preparation representative;
- Analysis Center representative;
- Data Center representative;
- Network representative;
- Scientific Product evaluation representative.

Appointed Members (5)

- Director of the Central Bureau;
- Absolute Gravity Data Base representative;
- IAG representative;
- BGI representative;
- IGFS representative.

Members at large (2)

- The members of the Directing Board elect the Members at large in a second round after their nomination or election, to insure a better geographical distribution.

3.3 Elections

IGETS associates are voting for the elected members.

The elected members have staggered four-year terms. There is no limit to the number of terms that a person may serve, however he/she may serve only two terms consecutively as an elected member. All IGETS associates are eligible to vote. Election is by a simple majority of votes received for each position. A vote by the Directing Board will resolve any situation of a tie.

3.4 IGETS Chair

The IGETS Chair is one of the Directing Board members and is elected by the Board for a term of four years with the possibility of reelection for one additional term. The Chair is the official representative of IGETS to external organizations.

3.5 Decisions

Most decisions by the Directing Board are made by consensus or by simple majority vote of the members present. In case of a tie, the Chair decides how to proceed. If a two-thirds quorum is not present, the vote shall be held later by electronic mail. A two-thirds vote of all Board members is required to modify the Terms of Reference, to change the Chair, or to replace any of the members before their normal term expires.

3.6 Meetings

The Directing Board meets at least annually or more frequently if meetings are called by the Chair or at the request of at least three Board members. The Board will conduct periodic reviews of the IGETS organization and its mandate, functions, and components.

4 Definitions

4.1 Associate Members

Individuals associated with organizations that support an IGETS component may become IGETS Associate Members. Associate Members take part in the election of the incoming members of the Directing Board.

4.2 Corresponding Members

IGETS Corresponding Members are individuals who express interest in receiving IGETS publications, wish to participate in workshops or scientific meetings organized by IGETS, or generally are interested in IGETS activities.

Attachment of the ToR

Analysis Centers

The primary Analysis Center, in charge of computing Level 2 products is hosted by the University of Polynesia (Tahiti, French Polynesia).

The secondary Analysis Center, in charge of computing the final gravity residuals is the EOST (Ecole et Observatoire des Sciences de la Terre) (Strasbourg, France).

Data Centers

The primary Data Center is the Information Systems and Data Center (ISDC) at GFZ (Potsdam, Germany), responsible for the collection of Levels-1, 2 and 3 data. The other datasets, including the historical products, are hosted at EOST (Strasbourg, France).

Central Bureau

The Central Bureau is hosted by the EOST (Strasbourg, France).

Directing Board (2020)

Chair of IGETS:	*H. Wziontek*, Germany
Director of the Central Bureau:	*J.-P. Boy*, France
Raw Data Preparation Represent.:	*V. Palinkas*, Czech
Analysis Center Representative:	*J.-P. Barriot*, France
Data Center Representative:	*C. Foerste*, Germany
Network Representative:	*H.-P. Sun*, China
Scientific Product Evaluation Rep.:	*C. Voigt,* Germany
Members at Large:	*D. Crossley*, USA
	J. Hinderer, France
	B. Meurers, Austria
Absolute Gravity Database Rep.:	*H. Wziontek,* Germany
IAG Representative:	*S. Pagiatakis,* Canada
BGI Representative:	*S. Bonvalot*, France
IGFS Representative:	*N. Sneeuw*, Germany

International Gravimetric Bureau
Bureau Gravimétrique International (BGI)

Director: **Sylvain Bonvalot** (France)

http://bgi.obs-mip.fr

Terms of Reference

Overview

The Bureau Gravimétrique International (BGI) has been created in 1951 as a scientific service of IAG during the IUGG (International Union in Geophysics and Geodesy) General Assembly for ensuring the collection, validation and archiving of all gravity measurements acquired at the Earth's surface and their distribution to scientific users. The technological and scientific evolutions which occurred over the following decades in the area of gravimetry (improvements in field, airborne and seaborne gravity meters, development of absolute gravity meters, space gravity missions, etc.) provided significant increases of the number, diversity and accuracy of the gravity field observables. Following these evolutions, BGI has contributed to provide original databases and services (products, documentation, tutorials, software…) for a wide international community concerned by the studies of the Earth gravity field. The strategic plan for period 2019-2023 will maintain this objective, ensuring a long term usability and sustainability of the highest-quality of gravity data.

BGI is an official service of the International Association of Geodesy (IAG) and is coordinated with others IAG services (IGeS, ICGEM, IDEMS, IGETS) by the International Gravity Field Service (IGFS). It also directly contributes within IAG to the activities of Commission 2 "Gravity Field" and Global Geodetic Observing System (GGOS). It is recognized by the International Council for Science (ICSU) successively as one of the services of the Federation of Astronomical and Geophysical Services (FAGS) and of the World Data System (WDS).

BGI has its central bureau in Toulouse, France (GET/OMP) and operates with the support of various French agencies (CNES, CNRS/INSU, IGN, IRD, SHOM, BRGM, IFREMER) and Universities (Toulouse, Paris, Strasbourg, Montpellier, Brest, Le Mans). BGI services also benefits from the close collaboration of other agencies from Germany (BKG), Italy (POLIMI), Greece (AUTH), Czech Republic (VÜGTK), Denmark (DTU) and USA (NGA).

Missions and objectives

The primary task of BGI is to improve the global knowledge of the Earth's gravity field through the collection, homogenization and validation of all available gravity measurements (relative or absolute) and make this information available to a large variety of users for scientific applications. With this aim, BGI holds and maintains for IAG the fundamental global databases of relative and absolute static gravity measurements and develops services to serve the scientific community. The most current services provided by BGI include:

- The supply of gravity data, reference stations, products, software and documentation.
- The validation and the archiving of gravity dataset and products provided to BGI and the attribution to data providers of a traceable international reference through a Digital Object Identifier (DOI).
- The realization and/or evaluation of global models (Earth Geopotential Model, World Gravity Map for instance) as well as regional data compilations carried out for gravity or geoid studies.

BGI also actively contributes to the definition of protocols, practices and recommendations aimed at improving the gravity data acquisition and processing and the realization of gravity surveys and networks. BGI is more specifically involved in the following actions:

- The definition and establishment of the “International Gravity Reference System & Frame (IGRS/IGRF)” promoted through the IAG Joint Working Group 2.1.1.
- The evaluation of new sensors for measuring absolute gravity (cold-atom absolute gravity meters).
- The support to the realization of national absolute gravity networks.

Finally, BGI also contributes with his collaborators to other research and development activities (software developments, research in geophysics and geodesy, etc.), to educational activities in gravimetry (summer schools, tutorials, etc.).

Product and services

Global databases of land and marine gravity data

The databases of relative measurements contain over 12 million of observations compiled and computerized mostly from land and marine gravity surveys. They have been extensively used for the definition of Earth gravity field models and for many applications in geodesy, satellite orbit computation, oceanography, geophysics, etc. They provide today the most precise information available on the Earth gravity field at short wavelengths complementary to airborne and satellite gravity measurements.

Global database of absolute gravity data

The database for absolute gravity measurements was set up in 2008 in cooperation between BGI and BKG (Bundesamt für Kartographie und Geodäsie, Germany) for collecting all available information on absolute gravity measurements acquired on Earth and for ensuring storage and long term availability of gravity data and processing details. It provides today the most complete information on existing absolute gravity stations and measurements (raw or processed data, description of stations, instruments, involved institutions, contacts, etc.). The database (AGrav) can be accessed by a web based interface which provides publicly available meta-data as well as complete datasets for community of users contributing to the archive. A simple exchange format was selected which includes all relevant information and is known by the majority of users avoiding additional effort. In this way the upload of absolute gravity data to the database can be done by the owner institutions, using a web based upload form.

Global database of gravity reference stations

Reference gravity stations established and connected to the former IGSN71 and Potsdam reference systems have been previously collected and archived at BGI. For several decades, these stations have provided the only available information on absolute gravity value for tying local or regional relative gravity surveys (terrestrial, marine, airborne) in a global reference frame. Even if a significant number of reference stations should have disappeared with time, this original IGSN71 database remains accessible and is still used in some countries for calibration of relative surveys. This global gravity reference network will be advantageously replaced by the International Gravity Reference System & Frame (IGRS/IGRF) based on the increasing network of actual absolute gravity measurements and made available from the above mentioned AGrav database.

Global or regional gravity grids and models

BGI also contributes to the realization of derived gravity products aimed at supporting studies of the Earth gravity field at global or regional scales. The products mostly used by scientific users are the digital global grids from the World Gravity Map (WGM) which represent the first gravity anomalies (Bouguer, isostatic and surface free-air anomalies) computed in spherical geometry taking into account a realistic Earth model (see Figure 1). They include 1 minute resolution terrain corrections computed from the contribution of most surface masses (atmosphere, land, oceans, inland seas, lakes, ice caps and ice shelves). The World Gravity Map is also available as a set of 3 global maps realized for the Commission for the Geological Map of the World (CGMW), UNESCO, International Union of Geodesy and Geophysics (IUGG) and International Union of Geological Sciences (IUGS). Maps available at: http://ccgm.org/en/16-catalogue. Other global or regional gravity models and products computed from other contributors may also be made available from the BGI website (contact BGI).

Other services

- Online tools for prediction gravity at a given site.
- Tools and software for data acquisition or validation
- Attribution of DOI (Digital Object Identifier) for relative and absolute gravity data set, products or software provided by contributors.

Key activities

Database & services

The current activities at BGI are mostly dedicated to consolidate and validate the IAG global gravity databases (relative and absolute measurements) and to develop pertinent and updated products and services for supporting long term sustainability and usability of gravity data for scientific purposes.

A new BGI website (to be achieved in 2020) will provide new services and information to both users and contributors. Among the new functionalities, it will include:

- a new version of the user interface for the Absolute gravity database (AGrav) providing improved functionalities and links between BGI and IGETS observations,
- a new version of the user interface for the Reference stations (former IGSN71 network),
- a DOI searching tool for identifying gravity sources in a given area.

Automatic procedures have been designed recently to assign an DOI reference number to any dataset archived in the BGI databases (either from recent or old gravity surveys). National agencies contributing in the acquisition or compilation of gravity measurements (from field, marine or airborne surveys) are thus encouraged to archive their data in a such way in order to update the data coverage and accuracy for each country or region and to better improve the recognition of their contribution in a global frame through the assignment of a DOI. New products are also currently under development at BGI for updating global or regional gravity products (maps and grids) for educational and research purposes.

Support for global gravity products, standards & networks

BGI contributes within IAG, and its components IGFS, GGOS and Commission 2 "Gravity Field", to several activities and Joint Working Groups aimed at improving the global knowledge and accuracy of the Earth gravity. It currently mostly brings its expertise and databases to the following projects:

IAG Joint Working Group 2.2.1 "Establishment of a global absolute gravity reference system"

This IAG Joint Working Group, launched during decade 2010 and chaired by H. Wziontek (BKG) and S. Bonvalot (BGI), aims at providing an accurate, homogeneous and long-term gravity reference at global scale based on absolute gravity observations. This project which leads to the definition and set-up of a new International Gravity Reference System & Frame (IGRS/IGRF) has within his objectives : (i) The establishment of a global network of core and reference stations where the gravity can be monitored continuously at the microGal level (10^{-8} m.s^{-2}) using the state-of-the-art of absolute gravity meters (corner cube or cold-atoms) and possibly in collocation with other geodetic techniques at GGOS Core stations ; (ii) The long-term traceability of the gravity measurements through international intercomparisons of absolute gravity meters ; (iii) The replacement of the former IGNS71 network by a modern network based on laboratory and field measurements of the absolute gravity. See Wilmes et al. (2016) and Wziontek et al. (2020) for more details.

IAG Joint Working Group 2.1.2 "Unified formats and processing software for high-precision gravimetry"

IAG Joint Working Group 2.2: "Validation of combined gravity model EGM2020"

Evaluation of new gravity sensors

BGI is involved in the evaluation of new gravity sensors such as those based on cold-atom technologies (Pereira et Bonvalot, 2016). It has accompanied the evaluation of the first commercial Absolute Quantum Gravimeter (AQG) developed by MuQuans company (France). It has also participated to the evaluation of a first hybrid absolute gravity meter (composed of accelerometers and cold atom sensor) designed by ONERA (France) for moving platform (shipborne or airborne). An airborne absolute gravity survey, including flights over sea and mountainous areas, has been carried out successfully in France for assessing and comparing the performances and accuracy of this novel instrument with other conventional airborne relative gravity meters and with ground surface marine and land gravity data (study in process). This activity also directly contributes to the new IAG Working Group "Novel Sensors and Quantum Technology for Geodesy (QuGe)" and more specifically to its sub-working group "Quantum gravimetry in space and ground".

Contribution to gravity surveys & networks

BGI associated research teams also contribute to the realization of gravity surveys and networks in the frame of national or international research projects with national agencies on the French territory or on other continents.

Other contributions

- Contribution to Newton's Bulletin: BGI contributes jointly with the International Service for Geoid (ISG) to the edition of this Bulletin which publish technical papers on gravity data acquisition and processing.
- Contribution to International summer schools on gravity or geoid in collaboration with ISG and IGFS.

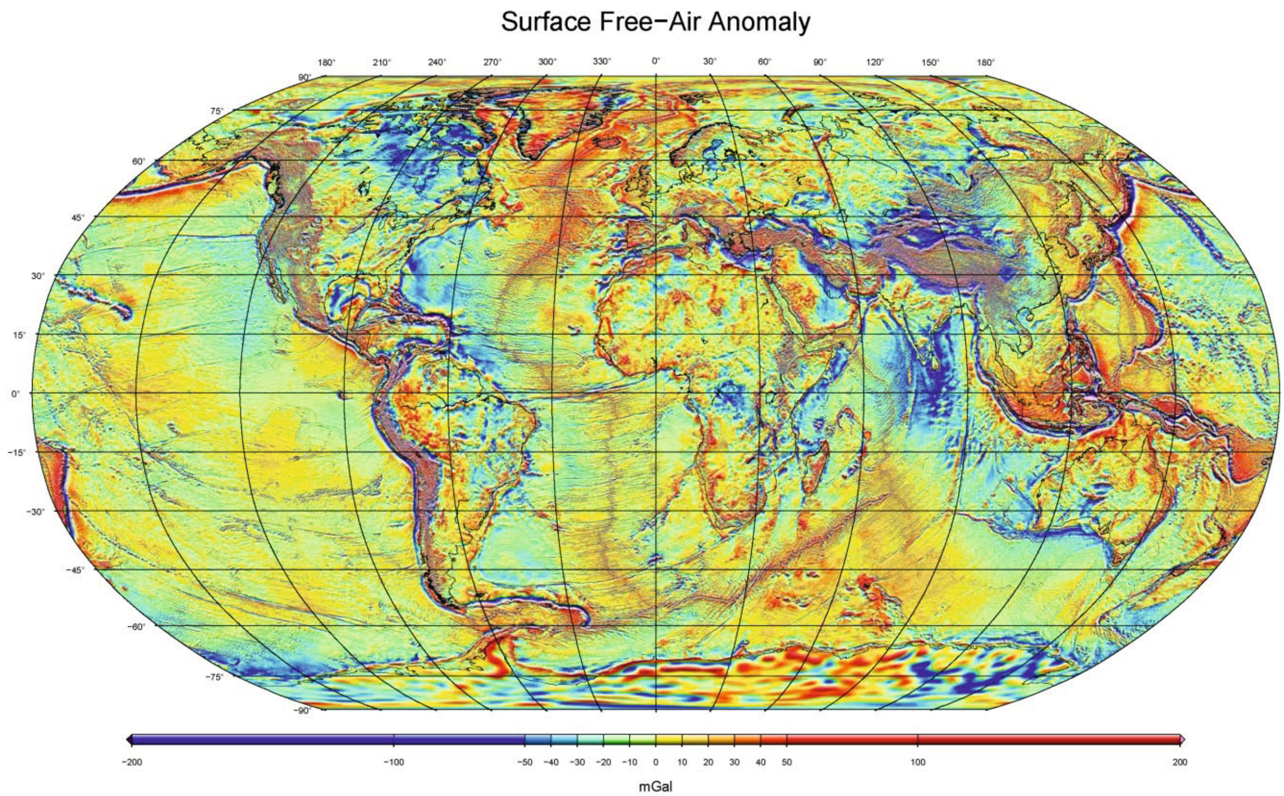


Fig. 1: Example of downloadable gravity product: 2 minutes global grid from the World Gravity Map (source BGI)

Users & contributors information

General terms of use

Data, products or software available at BGI are mostly dedicated to support scientific and academic activities. Digital gravity data or products are distributed free of charge to research or academic institutions or to data contributors according to the conditions given below. Other users, individual or private companies, are invited to specify in their request the expected use of the data and products. See BGI website for diffusion and charging policies.

- Access to non-confidential or non-proprietary relative gravity measurements is provided free of charge to public institutions or data contributors over geographic areas limited to 20°x20° or on the base of a maximum number of 10000 data points (land data) and/or 100000 data points (marine data). Retrieval of full data coverage for a whole country is not included in that case. All other requests (for larger datasets, for extended geographic area or for a whole country) as well as massive data retrieval will be subject to an evaluation by BGI who might require a specific protocol of use of the data or ask authorization of the proprietary Institutions. Charges might be applied.
- Access to the Absolute gravity database is provided free of charge. Database consultation and retrieval is done through the Web interfaces at BGI and BKG mirror sites. Confidential data or proprietary data may appear with restricted information (metadata only).
- Access to the Reference gravity stations database (IGSN71 network) is provided free of charge. Note that reference gravity stations (especially those determined and described decades ago) may have been destroyed or modified.
- Access to other additional services is also provided free of charge: global or regional gravity anomaly grids, Prediction of gravity value on Earth, Software, Documentation, etc.

Users of BGI data are invited to make reference to the specific DOI (Digital Object Identifier) provided by BGI along with the distributed data for each query.

Archiving and referencing data to BGI

The contribution of countries, agencies and scientists involved in surface gravity data acquisition (relative or absolute measurements from field, marine or airborne surveys) is essential for improving the global coverage and accuracy of the Earth gravity field and for contributing to the determination of the new International Gravity Reference Frame (IGRF). The archiving of such incoming gravity sets also enables BGI to better validate the gravity observations in a global reference frame and restore them in standard and unified formats useful for the end users.

Contributors interested in archiving their gravity observations or derived products as non-confidential or as proprietary data (to be defined by the contributors themselves) are invited to contact BGI. A **Digital Object Identifier (DOI)** will be delivered to any institution or author for archiving their own dataset resulting from gravity survey or gravity data compilation. This new service aims at ensuring a proper reference and recognition to the authors and institutions who have acquired or compiled gravity data and a better traceability of improvements in the global gravity data coverage from local or regional surveys. DOI attribution may be also extended to relevant software for gravimetric applications (data processing or modeling) or other related information (maps, grids, reports).

- Contributors with data from land, marine or airborne surveys are invited to contact BGI (bgi@cnes.fr). ASCII data files containing all necessary information and quantities are preferred (station coordinates, gravity measurements and accuracies; gravity corrections; reference geographic, height and gravity systems, etc.).
- Contributors with data from corner cube or cold-atom absolute gravity measurements are invited to contact either BGI (bgi@cnes.fr) or BKG (agrav@bkg.bund.de) Both laboratories and field measurements are welcome to contribute as parts of the reference and core station and of the national infrastructures building the new International Gravity Reference System & Frame.

For any contribution (relative or absolute gravity data), it is reminded that BGI will keep the status of diffusion (with or without restrictions of redistribution) as specified by the proprietary institution.

Structure and membership

Since 2003, BGI is one of the services of the International Gravity Field Service (IGFS) which coordinates within the IAG, the servicing of the geodetic and geophysical community with gravity field-related data, software and information.

The BGI central office (management, secretariat and technical staff) is located in Toulouse, France, in the premises of the Observatoire Midi-Pyrénées. Since 1998, BGI is supported by French agencies and works in close collaborations with universities and research teams involved in gravimetry and geodesy (see list below):

- Centre National d'Etudes Spatiales (CNES)
- Bureau de Recherches Géologiques et Minières (BRGM)
- Centre National de la Recherche Scientifique (CNRS)
- Institut National des Sciences de l'Univers (INSU)
- Institut National de l'Information Géographique et Forestière (IGN)
- Institut de Recherche pour le Développement (IRD)
- Service Hydrographique et Océanographique de la Marine (SHOM)
- Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER)
- Institut de Physique du Globe de Paris (IPGP)
- Ecole et Observatoire des Sciences de la Terre (EOST)
- Ecole Supérieure des Géomètres et Topographes (ESGT)
- Université de Toulouse (GET/OMP)
- Université de Montpellier (Géosciences Montpellier)
- Université de Brest (Géosciences Océan)

It also contribute in France to research groups and networks such as Groupe de Recherches en Géodésie Spatiale (GRGS), Réseau Sismologique et Géodésique Français (RESIF), Pôle de données Système Terre (DataTerra/ Form@Ter).

Each supporting organization has a representative member in the BGI Advisory Board. The Advisory Board (who also includes a representative member of IAG) contributes once a year to the orientation and evaluation of the BGI activities. The program of BGI activities is also evaluated and discussed by the IGFS Advisory Board at each IGFS meetings and IUGG General Assemblies. A partnership has been also established between BGI and the Federal Agency for Cartography and Geodesy (BKG), Germany, for the realization and the maintenance of the global database of absolute gravity measurements (AGrav) and with the Research Institute of Geodesy, Topography and Cartography (VUGTK), Czech Republic for metrology applications.

Contacts

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Wziontek H., Bonvalot S., Falk R., Gabalda G., Makinen J., Palinkas V., Rulke A., Vitushkin L. (2020). Status of the International Gravity Reference System and Frame. Journal of Geodesy (in press).

International Service for the Geoid (ISG)

President: **Mirko Reguzzoni** (Italy)
Director: **Daniela Carrion** (Italy)

http://www.isgeoid.polimi.it

Mission / Objectives

The main tasks of ISG are:

- to collect geoid estimates worldwide, when possible validate them, and disseminate them upon request among the scientific community. Other auxiliary data useful for the geoid determination may also be collected by ISG, without redistributing data that are already provided by other IAG services;
- to collect, test and when allowed distribute software for the geoid determination;
- to conduct researches on methods for the geoid determination, also defining optimal procedures for merging all available data and models;
- to organize international schools on geoid determination addressing both theoretical and practical topics, possibly every two years. During the schools, students are trained in the use of the relevant software for geoid computation;
- to support agencies or scientists in computing local and regional geoid models, especially in developing countries, also organizing special training courses;
- to disseminate training material and software on geoid computation, e.g. lecture notes of the schools;
- to issue the Newton's Bulletin, which has a technical and applied nature, collecting papers and reports on gravity and geoid;
- to establish and update a website to present the service activities, show and distribute the geoid models, software and publications, announce news and the organization of international schools on geoid determination.

Data and software given to ISG remain property of the authors, who decide upon the conditions of use and can allow, restrict or deny their distribution. ISG itself can indeed perform geoid computations within different projects, while remaining a non-profit institution.

Products

- Database of local and regional geoid models, in the form of grids or sparse points, stored and distributed in a homogeneous file format;
- Software archive for local geoid estimation, for terrain gravity effect calculation and for handling global models;
- Documentation on data and software;
- International schools and on request training courses on geoid computation;
- Lecture notes and other geoid related publications;
- Newton's Bulletin and the former IGeS Bulletin;
- Research results on gravity and geoid matters.

Future Programs/Development

Beyond institutional activities, the following research topics are worth of specific mention:

- computation of improved geoids for Italy and the Mediterranean area;
- integration of ground, air-borne, ship-borne and satellite gravity data for geoid modelling;
- integration of local, regional, continental and global geoid models;
- participation within GGOS to the study of the height datum unification problem;
- participation within IGFS to the validation of new global gravity models;
- study of improved methodologies for the determination of the geoid at local and global level.

Structure

ISG is an official IAG service that is coordinated by IGFS and is also related to the activities of the IAG Commission 2 on Gravity Field. Its structure, tools and activities are illustrated in the ISG reports to the Advisory Board of IGFS.

The Service is hosted by the Department of Civil and Environmental Engineering at Politecnico di Milano. ISG staff is currently composed by researchers and a secretary from Politecnico di Milano. They nominate, upon recommendation of IGFS, a President for its international representation and a Director for the operative management. In addition, the ISG advisors are scientists who have or have had an outstanding activity in the field of geoid determination and can also represent ISG in both research and teaching activities.

At present, the following distinguished scientists are ISG advisors:

N. Pavlis	(USA)
M. Sideris	(Canada)
J. Huang	(Canada)
R. Forsberg	(Denmark)
J. Ågren	(Sweden)
U. Marti	(Switzerland)
H. Denker	(Germany)
L. Sánchez	(Germany)
I. Tziavos	(Greece)
D. Blitzkow	(Brazil)
W. Featherstone	(Australia)
H. Abd-Elmotaal	(Egypt)
C. Hwang	(Chinese Taipei)

Finally, within the structure of ISG, Working Groups can be established for specific purposes, limited in time.

Permanent Service for Mean Sea Level (PSMSL)

Head: **E. A. Bradshaw** (UK)

http://www.psmsl.org

Development

Since 1933, the Permanent Service for Mean Sea Level (PSMSL) has been responsible for the collection, publication, analysis and interpretation of sea level data from the global network of tide gauges. It is based at the National Oceanography Centre (NOC), which on the 1st November 2019 began operating as an independent self-governing organization – a charitable company limited by guarantee. Funding is provided by the UK Natural Environment Research Council (NERC). The PSMSL continues to be one of the main data centres for both the International Association for Physical Sciences of the Oceans (IAPSO) and the IAG. The PSMSL operates under the auspices of the International Science Council (ISC) and reports formally to IAPSO's Commission on Mean Sea Level and Tides. The PSMSL is a regular member of the World Data System of ISC.

Mission/Objectives

Changing sea levels will have a major impact on human life over the next 100 years. We need mean sea level data to study climate change, the impact of human activities on densely populated areas, the economic impacts of sea level rise and to plan coastal engineering. The mission of the PSMSL is to provide the community with a full Service for the acquisition, analysis and interpretation of sea level data. Aside from its central role of operation of the global sea level data bank, the PSMSL provides advice to tide gauge operators and analysts. It occupies a central management role in the development of the Global Sea Level Observing System (GLOSS) and hosts important international study groups and meetings on relevant themes. The Sea Level Futures Conference that took place in July 2018 to mark the 85th Anniversary of the PSMSL is one such meeting.

Products

The database of the PSMSL contains over 72000 station-years of monthly and annual values of mean sea level (MSL) from over 2360 tide gauge stations around the world received from approximately 200 national authorities. On average, approximately 800 stations per year are entered into the database. This database is used extensively throughout the sciences of climate change, oceanography, geodesy and geology, and is the main source of information for international study groups such as the Intergovernmental Panel on Climate Change (IPCC).

Data for all stations are included in the PSMSL METRIC (or total) data set. The METRIC monthly and annual means for any one station-year are necessarily required to be measured to a common datum, although, at this stage, datum continuity between years is not essential. The year to-year datum checks become essential, however, if the data are subsequently to be included in the PSMSL 'Revised Local Reference (RLR)' component of the data set.

The 'Revised Local Reference (RLR)' dataset of the PSMSL contains records for which time series analysis of sea level changes can be performed. Long records from this dataset have been the basis of all analyses of secular changes in global sea level during the last century. The geographical distribution of longer RLR records contains significant geographical bias towards the northern hemisphere, a situation which is being rectified by the establishment of the GLOSS global sea level network.

The PSMSL is also responsible for the Higher Frequency Delayed Mode (HF DM) data set of sea level information from the GLOSS Core Network. This consists of the original sea level measurements from each site (typically hourly values) which provide a strategic backup to the MSL information of the main PSMSL data set.

The PSMSL received funding from the European Union Horizon 2020 EuroSea project to create an international archive to preserve and deliver Global Navigation Satellite Systems Interferometric Reflectometry (GNSS-IR) data and to integrate these data with existing sea level observing networks. GNSS-IR sensors provide an alternative method to observe sea level. As well as recording the sea level, these sensors will also provide vertical land movement information from one location.

In addition, the PSMSL provides a range of sea level products (e.g. interactive anomaly and trend maps, tables of sea level trends) for its users. These findings are input to national and international scientific study groups regularly. A range of training materials and software products are also made available via its web site which can be consulted for more information.

Structure/Governing Board Members

The PSMSL reports formally to the IAPSO Commission on Mean Sea Level and Tides (President Dr. *G.T. Mitchum*, USA). It is also served by an Advisory Group, which at present consists of Prof. *G. T. Mitchum* (University of South Florida, USA), Prof. *P. L. Woodworth*. (National Oceanography Centre, UK), Dr. *P. Knudsen* (Danish National Space Center), Dr. *R. Bingley* (Nottingham University, UK) and Dr. *G. Woppelmann* (Universite de La Rochelle, France). The Advisory Group is currently under review and membership will be updated in 2020. Suggestions for improvements in PSMSL activities may be sent directly to the PSMSL or via the IAPSO Commission or via any member of the Advisory Group.

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A. Hibbert
J. Williams
S. Williams
C. Wilson
L. J. Rickards (former Director)

IAG on the Internet

Szabolcs Rózsa, IAG Communication and Outreach Branch

http://www.iag-aig.org

The IAG maintains an Internet site, which is a valuable source of information not only about the Association itself, but also about its scientific disciplines. The primary goal of the website is to communicate with the IAG members, and make information available to the wider Geoscience community in the world as a whole.

Since the maintenance of the IAG website belongs to the activities of the Communication and Outreach Branch (COB) it is still hosted at the Department of Geodesy and Surveying of the Budapest University of Technology and Economics (BME), Budapest, Hungary. The geographical distribution of the visitors of the IAG website can be seen on Figure 1 for the period of January, 2019 to June 2019.

The layout of the website was redesigned in 2019 to fully support handheld devices, such as tablets, smartphones, etc.

Topic of the Month

The Topic of the Month section of the opening page aims to promote important scientific achievements and activities to the wider public. The latest scientific results, the establishment of international and interdisciplinary research projects and all other information, which may have a great impact on the geodetic community, can be posted to this section of the website.

Since the COB intends to publish a new topic in each month, Geodesists are kindly encouraged to submit new topics to the COB e-mail address: iagcob@iag-aig.org

The Topics of the Month must include an image and a short introduction, too. Both are published on the opening page of the website, and more details are given on separate pages.

Publishing on the IAG Website

The IAG COB encourages all the IAG Members and Geodesists in general to publish information on the IAG website. News, conference calls, job announcement, etc. can be submitted to the IAG COB for publication. Contributions can be sent to the following e-mail address: iagcob@iag-aig.org.

IAG on Social Media

In order to address the younger generations, the COB has opened the IAG page on Facebook and Twitter. As of June 10, 2020, the Facebook page http://www.facebook.com/ InternationalAssociationOfGeodesy has 1767 'likes'. The age distribution of the likers can be seen on Figure 2. The Twitter site of IAG is available at http://www.twitter.com/iag_cob. As of June 10, 2020 IAG has 804 followers on Twitter. We would like to encourage everyone who is interested in Geodesy to follow these pages, since the latest information published on the IAG website are available on Facebook and Twitter, too. The followers of these pages are automatically notified about the latest IAG news.

However, our appropriate presence on the social media needs more frequent news on Geodesy and IAG. We would like to encourage IAG members and geodesists in general to provide us input to be published on these sites! Please feel free to contact the COB for publishing such geodesy related information, because it really helps to improve the outreach activities of IAG.

We do appreciate your help and cooperation!

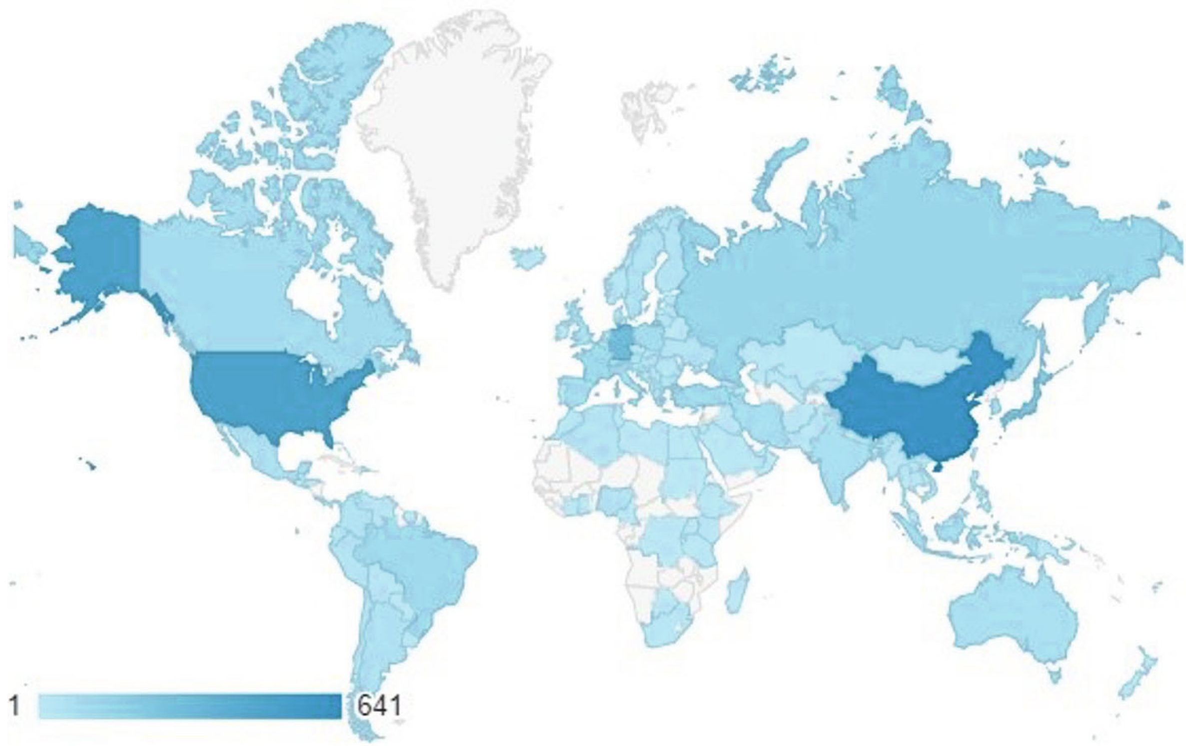

Figure 1. The geographical distribution of the page visits of the IAG website (http://www.iag-aig.org) between January, 2019 and June, 2019.

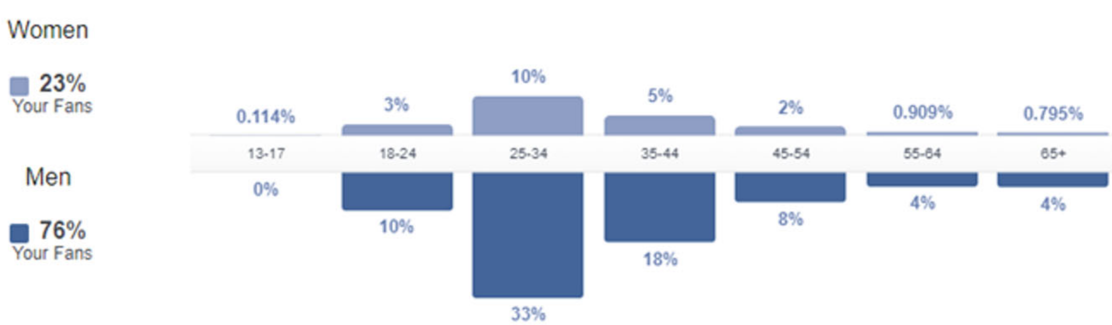

Figure 2. The age distribution of Facebook likers (above: 25% of likers are women, below: 75% of likers are men)

Publications of the International Association of Geodesy (IAG)

I. Journal of Geodesy

Twelve issues per year:
Annual subscription or sale by unit (Springer-Verlag)
Springer Verlag
Tiergartenstrasse 17
D – 69121 Heidelberg
Germany
www.springer.com

II. Geodesist's Handbook

Quadrennial special issues of the Journal of Geodesy, published since 1980, contain the present IAG laws and rules, summaries of the latest IAG General Assemblies, and the structures and the program descriptions for all the IAG components of the respective upcoming period.

III. IAG Symposia Series

Peer reviewed proceedings of selected IAG Symposia. Available at Springer-Verlag (see under I.). Latest issues:

Vol. 146: van Dam, T. (Ed., 2017) REFAG 2014 Proceedings of the IAG Commission 1 Symposium Kirchberg, Luxembourg, 13–17 October, 2014

Vol 147. Freymueller, Jeffrey T., Sánchez, Laura (Eds., 2018) International Symposium on Earth and Environmental Sciences for Future Generations, Proceedings of the IAG General Assembly, Prague, Czech Republic, June 22- July 2, 2015

Vol 148. Vergos, Georgios S., Pail, Roland, Barzaghi, Riccardo (Eds., 2019) International Symposium on Gravity, Geoid and Height Systems 2016, Proceedings Organized by IAG Commission 2 and the International Gravity Field Service, Thessaloniki, Greece, September 19-23, 2016

Vol 149. Freymueller, Jeffrey T., Sánchez, Laura (Eds., 2019) International Symposium on Advancing Geodesy in a Changing World, Proceedings of the IAG Scientific Assembly, Kobe, Japan, July 30 – August 4, 2017

Vol 150. Mertikas, Stelios P., Pail, Roland (Eds., 2020) Fiducial Reference Measurements for Altimetry, Proceedings of the International Review Workshop on Satellite Altimetry Cal/Val Activities and Applications

Vol 151. Novák, P., Crespi, M., Sneeuw, N., Sansò, F. (Eds., 2021) IX Hotine-Marussi Symposium on Mathematical Geodesy, Proceedings of the Symposium in Rome, June 18 – 22, 2018

IV. Travaux de l'Association Internationale de Géodésie (IAG Reports)

The IAG Reports (Travaux de l'Association Internationale de Géodésie) are published on the occasion of the IAG General and Scientific Assemblies every two years and contain the reports of all IAG components and sub-components. They were published as printed volumes until 2003 (since 1991 also available in digital form) and since 2005 online only at *http://www.iag-aig.org/travaux* and at http://office.iag-aig.org/iag-publications-reports-position-papers. Printed versions may be ordered at the IAG Office (iag.office@maanmittauslaitos.fi).

Geodetic Data Centres

The IAG Communication and Outreach Branch (COB) compiles and maintains a list of **Geodetic Data Centres**. All data compiled in this list are regularly revised by the IAG National Correspondents.

Considering the fact that addresses are subjected to frequent changes, the directory is stored as a file in the web to sustain the possibility of updates whenever useful. All information is also available at the IAG Website (*https://www.iag-aig.org/geodetic-data-centers*).

All available data are stored in the IAG Website as soon as the responsible National Correspondent sends them to the IAG COB (address see below). All National Correspondents are kindly asked to inform the COB[1] on any change.

Educational Establishments for Geodesy

The IAG Communication and Outreach Branch (COB) compiles and maintains a list of addresses of Educational Establishments for Geodesy. All data compiled in this list are regularly revised by the IAG National Correspondents.
Considering the fact that addresses are subjected to frequent changes, the directory is stored as a file in the web to sustain the possibility of updates whenever useful. All information is also available at the IAG Website (*https://www.iag-aig.org/educational-institutions*).

All available data are stored in the IAG Website as soon as the responsible National Correspondent sends them to the IAG COB (address see below). All National Correspondents are kindly asked to inform the COB[1] on any change.

Geodetic Publication Series

The IAG Communication and Outreach Branch (COB) compiles and maintains a list of **Geodetic Publication Series**. All data compiled in this list are regularly revised by the IAG National Correspondents.

Considering the fact that addresses are subjected to frequent changes, the directory is stored as a file in the web to sustain the possibility of updates whenever useful. All information is also available at the IAG Website (*https://www.iag-aig.org/publication-series*).

All available data are stored in the IAG Website as soon as the responsible National Correspondent sends them to the IAG COB (address see below). All National Correspondents are kindly asked to inform the COB[1] on any change.

IAG Directory

Due to the General Data Protection Regulation, IAG ceases to publish the IAG Directory. For contact details, please contact the IAG Office at iag.office@maanmittauslaitos.fi.

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