Commission 2 - Gravity Field

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President: Srinivas Bettadpur (USA)
Vice President: Tao Jiang (China)

Commission 2 website - https://geodesy.science/com2/

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JWG 2.2.1 Comprehensive gravity data integration for the sub-cm geoid/quasi-geoid modelling
(joint with IGFS, ISG)
Chair: Ismael Foroughi (Canada)
JWG 2.3.1 Spatial Leakage Mitigation in Satellite Gravimetry
(joint with ICCC)
Chair: Eva Boergens (Germany)

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JSG 3.1 Model representation and geodetic signature of solid-Earth rheology in surface loading problems
(joint with Comm 1 and Comm 3)
Chair: Lambert Caron (USA)
JSG T.42 Theoretical developments and applications of combined methods for a better understanding of the Earth's lithospheric formation, structure, and dynamics
(joint with Comm 2 and Comm 3)
Chair: Robert Tenzer (China-Hong Kong)

2 Activities during the reporting period 2023-2025

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The international geodetic community has made significant progress across various domains of gravity and geoid research. SC2.1 led international comparisons of absolute gravimeters, including CCM.G-K2.2023 in the USA and EURAMET.M.G-K2.2023 in Germany, with participation from numerous institutions. Regional gravimetry efforts included airborne surveys in Australia, quantum gravimeter deployment in Canada, and the establishment of gravity stations in Brazil, Paraguay, Uruguay, and the Dominican Republic. European countries such as Poland, Slovakia, Denmark, and the Czech Republic modernized their gravity control networks, while quantum gravimetry projects like QuGrav and EQUIP-G gained traction. SG2.1.1 emphasized mobile platform gravimetry, with the GRAV-D project completing airborne surveys in the US and expanding into Canada. DTU and German teams explored quantum and strapdown gravimeters, and the BalMarGrav project continued marine-based gravity mapping. JWG2.1.1 re-established the Absolute Gravity Database (AGrav) and advanced the International Terrestrial Gravity Reference Frame (ITGRF), integrating global datasets and quantum gravimeter comparisons.

SC2.2 contributed to the International Height Reference System (IHRS) and Frame (IHRF), coordinating with the new IHRF Coordination Center. Activities included geopotential estimation using global and regional models and GNSS/levelling data, with sessions organized at GGHS2024 and future meetings planned in India. JWG2.2.1 focused on sub-centimeter geoid modelling by integrating diverse gravity datasets, topographic corrections, and machine learning. Key projects included GEOID2022 in North America, regional harmonization in India and Italy, and vertical datum modernization in South America led by SIRGAS. Taiwan and Norway contributed coastal and terrain-aware modelling. JSGT.47 addressed theoretical refinements in height definitions and standardization, including chrono-geodesy and levelling data integration, supported by publications and workshops.

SC2.3 supported GRACE/GRACE-FO operations and the development of future missions GRACE-C (launch 2028) and NGGM (launch 2032), which together form the MAGIC constellation aimed at delivering high-resolution gravity data. GRATTIS and CARIOQA missions will demonstrate advanced accelerometry and quantum sensing. JWG2.3.1 investigated spatial leakage in satellite gravimetry, identifying sources and resolution limits, with a review paper and PhD funding proposal in progress.

SC2.4 regional initiatives made notable advances. In Europe, leadership transitioned to J. Schwabe, and due to data confidentiality, a new European Gravimetric Geoid (EGG) must be rebuilt. South America collected over 924,000 gravity points and developed new geoid models like SAM_GEOID2023 and GEOID-SP-2024, supported by training and collaboration through geoid schools and SIRGAS. North and Central America saw collaboration between Canada, the USA, and Mexico on GEOID2022 and NAPGD2022, integrating multiple data sources and developing dynamic geoid models. Africa developed new gravity databases (AFRGDB V2.3, V3.0) and Moho models, addressing crustal density effects and relativistic height systems, though data scarcity remains a challenge. In the Asia-Pacific region, SWOT and GNSS-R data supported coastal geoid modelling, with workshops in the Philippines and leadership from Taiwan and China in geoid unification and validation.

SC2.5 advanced satellite altimetry for geodesy, oceanography, and climate studies. SWOT data enabled high-resolution gravity and bathymetry modelling, and machine learning improved bathymetric predictions. GNSS-R missions like PRETTY demonstrated new altimetric capabilities. SG2.5.1 produced high-resolution water level datasets using FFSAR altimetry, validated by SWOT, supporting hydrological and coastal studies. SG2.5.2 developed the JASTER tool for automated Jason altimetry processing and began drought impact evaluations in Indonesia. SG2.5.3, led by David Sandwell, focused on SWOT-derived gravity and bathymetry, revealing tectonic features and improving seamount catalogues. SG2.5.4 produced new global datasets (IAS2024, CUGB2023GRAD), presented at major conferences, and engaged with government agencies on climate and security applications.

SC2.6 supported mass transport studies using GRACE/GRACE-FO and COST-G RL02 solutions, with international meetings advancing understanding of Tibetan

Plateau dynamics and sea level rise. SG2.6.1 organized TibXS symposia and published special issues on hydrology, crustal deformation, and climate change, using GNSS, GRACE, and altimetry to monitor water storage, land motion, and subsidence.

JSGT.42 explored combined methods for lithospheric studies, including stress field evolution under supercontinents, spherical Slepian functions for sea level analysis, a new African Moho model, gravimetric forward modelling software, mantle viscosity estimation, GNSS-R for sea level studies, high-resolution Moho modelling, relativistic geodesy with atomic clocks, and dynamic topography modelling. These efforts contribute to improved geophysical models and integration of satellite and terrestrial data.

3 SC 2.1 Terrestrial gravimetry for the needs of geosciences and metrology

Chair: Przemysław Dykowski (Poland)
Vice-Chair: Ezequiel Antokoletz (Argentina/Germany)

International Comparisons of Absolute Gravimeters

- CCM.G-K2.2023 Key Comparison and Supplemental Study
  Table Mountain Geophysical Observatory (TMGO), Boulder, Colorado (USA), August/September 2023
  The Key Comparison of Absolute Gravimeters, CCM.G-K2.2023, and a Supplemental Study were conducted at the Table Mountain Geophysical Observatory (TMGO) near Boulder, Colorado between 21 August and 29 September, 2023 with 30 Absolute Gravimeters from 27 institutions.

In August of 2024 the Draft B report was submitted to the CCM-WGG working group for evaluation.

- EURAMET Key Comparison of Absolute Gravimeters EURAMET.M.G-K2.2023 and Additional Comparison
  Wettzell (Germany), May/June 2024
  The EURAMET Key Comparison of Absolute Gravimeters EURAMET.M.G-K2.2023 and Additional Comparison (WETCAG-2024) was conducted at the Geodetic Observatory Wettzell (Germany) from May 21st to June 20th 2024 with 17 Absolute Gravimeters from 15 institutions.

In May of 2025 the Draft A report was submitted to the participants, results are planned to be discussed during the CCM-WGG meeting in June of 2025.

Organization/participation of/in meetings and conferences

SC2.1. as well as associated JWGs members participated in multiple international meeting related to gravimetry or with dedicated sessions related to gravimetry:

- 20th International Symposium on Geodynamics and Earth Tides, Strasbourg, France, August 25-30, 2024
- Gravity Geoid and Height Systems 2024, Thessaloniki, Greece, 1-5 September, 2024
- JWG 2.1.1. meeting at Gravity Geoid and Height Systems 2024, Thessaloniki, Greece, 1-5 September, 2024
- EGU2024, Vienna, Austria, 14-19 April, 2024
- EGU2025, Vienna, Austria

Regional activities in gravimetry

Australia:

- Geoscience Australia (GA), in collaboration with the governments of Victoria, New South Wales, and South Australia, has undertaken airborne gravity surveys across the three states. These surveys began in 2020 and are scheduled for completion by 2025.
  In parallel, GA launched the analysis-ready-gravity-data-workflow GitHub page (https://github.com/GeoscienceAustralia/analysis-ready-gravity-data-workflow) in 2024 to support the analysis of data for the Australian Gravimetric Quasi Geoid (AGQG). This workflow integrates all available gravity observations across Australia, including terrestrial, airborne, and satellite altimetry data.

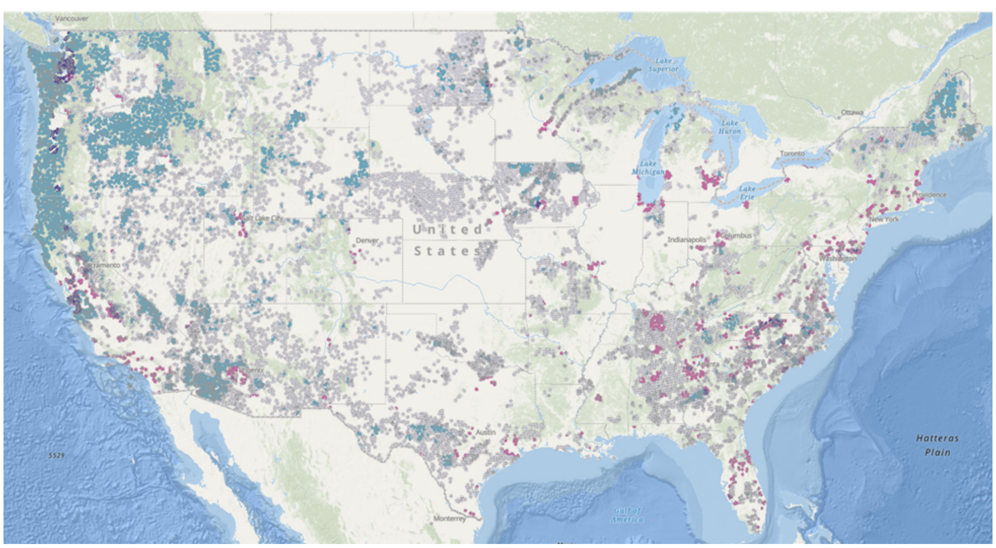

Fig. 1. Map of priority areas for terrestrial gravity measurements. Pink hexagons indicate high population density, blue indicate relatively high geoid uncertainty, and purple indicate both high population and geoid uncertainty.

North America:

- Canada: AQG-B13 quantum gravimeter acquisition by NRCan
  The Canadian Geodetic Survey (CGS) acquired an Exail B-13 Absolute Quantum Gravimeter in Dec. 2024. The instrument is installed at the Canadian Absolute Gravity Station (CAGS) in Cantley, Quebec, Canada and CGS is in the process of testing and characterizing the instrument.
  An absolute gravity point was established at the Prince George airport in Prince George, British Colombia, Canada to support a gravity tie for the US GRAV-D Follow-On airborne gravity survey over British Columbia.
  Plans are underway to tear down and rebuild the Canadian Absolute Gravity Station (CAGS) in Cantley, Quebec, Canada later in 2025 or early in 2026. The proposed rebuild will provide an additional 7 gravity piers and support for hosting international absolute gravity comparisons in the future.

- United States: The National Geodetic Survey (NGS) completed the data collection phase of its "Gravity for the Redefinition of the American Vertical Datum" (GRAV-D) project, collecting airborne gravity over the United States and its territories. A total of 4800 lines were flown over 15 years at a nominal spacing of 10 km. Analysis of cross-over and repeat lines indicates an overall accuracy of about 1.5 mGal in smooth terrain (and between 2 to 3 mGal in mountainous terrain). The data were used in the certation of new vertical datums for the North American region which are due to be released in late 2025/early 2026.
  A joint project between NGS and the National Geospatial Intelligence Agency (NGA) – the "GRAV-D Follow On Project" – is currently underway to collect airborne gravity in Canada (and eventually, Mexico) to collect data in the border regions with the United States.
  NGS is in its third year of collecting terrestrial relative gravity data in select regions of the U.S. as part of its "RelGrav" project to densify gravity information for geoid improvement. Target areas so far (based on regions with little or no current gravity data and near higher population centers, see Figure 1) include Iowa and North Carolina– with over 2000 observations collected.
  In addition, the GeMS Absolute Gravity project is collecting repeat A10 gravity observations at select primary sites on a five-year cycle (the conterminous, "lower 48" states are divided into four quadrants, with Alaska, Hawaii, and other territories forming a "fifth"). The second cycle of measurements begins in 2025.
  Three pairs of gPhoneX continuous relative gravity meters are deployed at three sites in Alaska to monitor seasonal cycle details as the long term signal from glacial retreat is recorded.
  Finally, FG5X 102 at the Table Mountain Geophysical Observatory has been upgraded with a horizontally mounted XY detector to measure Coriolis accelerations and verticality offsets in real time. This work is in collaboration with Micro-g LaCoste.

South America:

- Brazil: In Brazil, two absolute stations were stablished in the year of 2023. The first in Chuí_SESC in Rio Grande do Sul state and the second in Rio Brilhante in Mato Grosso do Sul state.

- Paraguay: Between the years of 2022 and 2023, 22 absolute stations were establibhed in Paraguay. The stations were measured by the Universidad Nacional de Asunción (FIUNA/PY) and EPUSP-PTR supported by IGC and CENEGEO.

- Uruguay: Four new absolute stations were established and three were reoccupied in April 2023, adding up to 7 absolute stations. The Military Geographic Institute (IGM/UY) and EPUSP-PTR supported by IGC and CENEGEO measured the stations. Previous observations were made with JILAG3.

- Dominican Republic: The Ministry of Energy and Mines (MEN) with National Geological Service (SGN) at Dominican Republic, with CENEGEO – Centro de Estudos de Geodesia, Brazil, have been working in the last few years in order to establish the Local Reference Gravity (LRG) in the country as well as to improve the gravity coverage. A total of 12 absolute measurements have been accomplished.

Europe:

- Poland:
  Gravity control:
  In 2023 works in Poland were initiated to re-measure the Polish gravity control. In 2024 absolute gravity measurements and vertical gravity gradient determinations were done with FG5-230 (WUT, Warsaw) on 29 fundamental stations (indoor). Also in 2024 measurements were initiated on the base stations (outdoor). Up to now absolute gravity measurements with A10-020 (IGiK, Poland) were completed on 41 stations and vertical gravity determinations on 61 stations. Measurements are controlled by the gravity reference function realised by the iGrav-027 superconducting gravimeter at Borowa Góra Observatory.
  International projects:
  Within the years 2022-2024 BalMarGrav (Homogenized marine gravity maps of southern and eastern Baltic Sea for modern 3D applications in marine geodesy, geology and navigation) an international project funded within the Interreg program (https://interreg-baltic.eu/project/balmargrav/). Terrestial and marine gravity measurements were carried out within the project. Project carried out by the Institute of Geodesy and Cartography (Warsaw, Poland).
  In November of 2024, the QuGrav (Advances in the use of quantum technologies for terrestrial determinations of Earth's gravity) project was initiated. Extensive testing of the AQG-B07 quantum gravimeter is planned within the project jointly with Exail (instrument manufacturer). Project carried out by the Institute of Geodesy and Cartography (Warsaw, Poland).
- Slovakia:
  In the years 2023 and 2024 modernization of the Slovak gravity control was carried out with the use of the A10-020 absolute gravimeter (Institute of Geodesy and Cartography, Poland). Measurements were carried out on nearly 90 field gravity stations. Work was ordered and supervised by the Slovak National Mapping Authority (GKU).

- Denmark:
  In summer 2023 an airborne gravity survey in Iceland and Greenland was carried out utilizing the GIRAFE quantum gravimeter from ONERA and the iMAR classical strapdown gravimeter from DTU.
- Czech Republic:
  Dedicated measurement campaigns were carried out in order to implement FG5 gravimeters for outdoor usage (under a tent) by the Research Institute of Geodesy, Topography and Cartography. Additionally dedicated campaings were carried out with Land Survey Office to re-new vertical gravity gradients on the national gravity network.

Activities in Quantum Gravimetry (can be linked to IAG QuGe Project)

- AQG operator meeting 2024: workshop and joint measurements in Hannover
  Organized by the GFZ Section 4.4 "Hydrology" and under the umbrella of the Collaborative Research Centre "TerraQ" (SFB 1464), the world's first workshop on the "Absolute Quantum Gravimeter" (AQG, Exail) took place from 22 to 26 of January 2024 at Leibniz University Hanover (Germany), together with a joint measurement session from 5 AQG instruments. It was the first meeting of the community of quantum gravimeter operators after this instrument became available as the first commercially new type of absolute gravimeter. It was announced in the IAG newletter February 2024.
- AQG gravimeter comparison in Borowa Góra (Poland) in 2025
  As a part of the QuGrav project in Poland (mentioned above), a quantum gravimeter comparison was organised at the Borowa Góra Geodetic-Geophysical Observatory in Poland. Total of 4 AQG sensors participated in the comparison, same gravimeters that participated in the comparison in Hannover in January of 2024.
- On 1st of June 2025, the EQUIP-G (EQUIP-G - European QUantum Infrastructure Project for Gravimetry) project was started (https://cordis.europa.eu/project/id/101215427) focused on advancing quantum sensors. Among 19 institutions in the consortium, multiple SC2.1. and accociated JWG members take active part in the project. Activities within the project will exploit the link to ITGRF and IAG activities. Project is planned for 48 months with a total budget of 25M EUR.

Other relevant activities

- Re-establishment of Absolute Gravity Database (AGrav) at BGI and BKG - June 2024
  After the AGrav database was offline for more than 2 years, we are happy to inform you that it is now successfully re-established at BGI jointly with BKG, with the technical support of Observatoire Midi-Pyrénées (SEDOO service). The database is considered an important part of the upcoming International Terrestrial Gravity Reference Frame (ITGRF), the main task of IAG Joint Working Group JWG 2.1.1 for the current term. The whole dataset existing at AGrav until Feb 2022 is now accessible with a modern Web interface:

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SG 2.1.1 Gravity Observations from Mobile Platforms

Chair: Derek van Westrum (USA)
Vice-Chair: Neda Darbeheshti (Australia)

Overview

Gravity observations from mobile platforms (marine and airborne) continue to evolve and diversify as new sensors become available and practical. The National Geodetic Survey (USA) has completed its 15-year project, Gravity for the Redefinition of the Vertical Datum (GRAV-D) to support its new gravimetric geoid. The Danish Technical University (DTU) is exploring the use of airborne quantum gravimeters, while a German team is comparing stabilized platform meters with strapdown IMU systems. The BalMarGrav teams continues to produce maps for geodesy from their marine-based gravity observations.

- **USA**
  The National Geodetic Survey (NGS) completed the data collection phase of its "Gravity for the Redefinition of the American Vertical Datum" (GRAV-D) project, collecting airborne gravity over the United States and its territories. A total of 4800 lines were flown over 15 years at a nominal spacing of 10 km. Analysis of cross-over and repeat lines indicates an overall accuracy of about 1.5 mGal in smooth terrain (and between 2 to 3 mGal in mountainous terrain). The data were used in the certation of new vertical datums for the North American region which are due to be released in late 2025/early 2026.
  https://geodesy.noaa.gov/GRAV-D/
  https://beta.ngs.noaa.gov/NAPGD2022/
  A joint project between NGS and the National Geospatial Intelligence Agency (NGA) – the "GRAV-D Follow On Project" – is currently underway to collect airborne gravity in Canada (and eventually, Mexico) to collect data in the border regions with the United States.
- **Denmark**
  Jensen, T. E., Dale, B., Stokholm, A., Forsberg, R., Bresson, A., Zahzam, N., Bonnin, A., and Bidel, Y., Airborne gravimetry with quantum technology: observations from Iceland and Greenland, Earth Syst. Sci. Data, 17, 1667–1684, https://doi.org/10.5194/essd-17-1667-2025, 2025.
- **Germany**
  Felix Johann, Hannes Eisermann, Graeme Eagles, A comparison and combination of stable platform and strapdown airborne gravimeters, Journal of Applied Geophysics, Volume 241, 2025, https://doi.org/10.1016/j.jappgeo.2025.105826.
- **International**
  The BalMarGrav project: Wilde-Piorko et al.
  https://interreg-baltic.eu/wp-content/uploads/2023/10/report_modern_final.pdf

4 SC 2.2: Geoid, Physical Height Systems and vertical datum unification

Chair: Georgios S. Vergos (Greece)
Vice-Chair: Rossen S. Grebenitcharsky (Kingdom of Saudi Arabia)

SC2.2 consists of a steering committee, through which participation to the various research activities are promoted. Within SC2.2 a JWG, with IGFS and ISG, namely JWG2.2.1: Comprehensive gravity data integration for the sub-cm geoid/quasi-geoid modelling" has been established. It focuses on investigation of different spectral and spatial combination methods to integrate scalar- and vector-valued gravity observations; on the contribution of satellite-only or combined global gravitational models, for their efficient integration with high-frequency gravity observations provided by land-level sensors; examining different data combination methods on the accuracy of the geoid/quasi-geoid models affected; Exploring the potential use of GNSS/levelling observations for optimizing the combination of various types of gravity observations; on investigating optimal techniques for evaluation of the full (spatial) or band-limited topographic corrections to each type of gravity observations; on the investigation of the complexity of gravity field observations, and its effect on their interpolation and downward continuation; on the use of very high degree/order synthetic global gravitational model, e.g., up to 21600, to test different combination techniques, and omission and commission errors; on sharing experimental data and software tools dedicated to gravity data integration and evaluation of topographic corrections on gravity data and computed quasi-/geoid in a repository ; on investigating the potential benefits of Machine Learning and Artificial Intelligence for gravity data interpolation and integration. Moreover, a JST with IGFS, namely "JSGT.47: Height Datum: Definition, New Concepts, and Standardization" has been established with the objective to: consolidate the theory of physical heights, including the proper use of normal heights as related to the geoid; and to suggest recommendations regarding the practical use of normal heights related to the geoid.

Activities during the period of 2023-2025

During the reporting period, SC2.2 activities focused mainly on the interaction with the newly established International Height Reference Frame Coordination Center (IHRF CC), which was founded as an IGFS entity in December 2023. The scope was to contribute to the realization of the International Height Reference System by contributing to the estimation, employing various approaches, of potential values for the IHRF core sites. The main steps for the determination of IHRF geopotential values at IHRF sites have been determined. The activities are based on a geopotential determination based on a) global geopotential models only, b) global geopotential and topography potential models and c) local/regional geoid/quasi-geoid models either available at the SC2.2 and IHRF CC participating members and the International Service for the Geoid reprository. Already, a number of presentations and a peer-reviewed journal paper have been prepared.

Peer-Reviewed Publications

1. Sánchez, L., Barzaghi, R., Vergos, G. (2024). Operational Infrastructure to Ensure the Long-Term Sustainability of the International Height Reference System and Frame (IHRS/IHRF). pp. 1–10. https://doi.org/10.1007/1345_2024_250.
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5. Vergos, G.S., Tziavos, I.N., Mertikas, S., Piretzidis, D., Frantzis, X., Donlon, C. (2024). Local Gravity and Geoid Improvements around the Gavdos Satellite Altimetry Cal/Val Site. *Remote Sens.*, 16, 3243. https://doi.org/10.3390/rs16173243.

Conference Presentations

- Ampatzidis, D., Vergos, G.S. (2024). The temporal evolution of the physical heights: Theoretical and practical considerations under the prism of the International Height Reference Frame realization. Presented at the GGHS2024 Joint Section 2, IGFS and GGOS Symposium "Gravity, Geoid and Height System 2024", September 4–6, Thessaloniki, Greece.
- Li, X., Santos, M., Novák, P., Vergos, G.S., et al. (2024). Height datum: Definition, New Concepts, and Standardization. Presented at the GGHS2024 Joint Section 2, IGFS and GGOS Symposium "Gravity, Geoid and Height System 2024", September 4–6, Thessaloniki, Greece.
- Sánchez, L., Barzaghi, R., Vergos, G.S. (2023). Operational infrastructure to ensure the long-term sustainability of the IHRS/IHRF. Presented at the 28th IUGG General Assembly, July 11–20, 2023, Berlin, Germany.
- Sánchez, L., Barzaghi, R., Huang, J., Ågren, J., Vergos, G.S., and the IHRF Computation Team (2023). A first solution for the International Height Reference Frame (IHRF). Presented at the 28th IUGG General Assembly, July 11–20, 2023, Berlin, Germany.
- Sánchez, L., Huang, J., Barzaghi, R., Vergos, G.S. (2023). Advances in the determination of a global unified reference frame for physical heights. Presented at the 28th IUGG General Assembly, July 11–20, 2023, Berlin, Germany; and at the 2023 EGU General Assembly, April 23–28, Vienna, Austria.
- Sánchez, L., Barzaghi, R., Vergos, G.S. (2024). Towards a first solution for the International Height Reference Frame (IHRF). Presented at the GGHS2024 Joint

Section 2, IGFS and GGOS Symposium "Gravity, Geoid and Height System 2024", September 4–6, Thessaloniki, Greece.
- Vergos, G.S., Sánchez, L., Barzaghi, R. (2024). IHRF Coordination Center, a newly established IAG/IGFS component to ensure the sustainability of the IHRS/IHRF. Presented at the 2024 EGU General Assembly, April 14–19, 2024, Vienna, Austria.
- Vergos, G.S., Grigoriadis, V.N., Natsiopoulos, D.A., Andritsanos, V.D., Paraskevas, M., Papadopoulos, N. (2024). Preliminary results on the new Hellenic Geoid 2024 in support of a geoid-based VRF. Presented at the GGHS2024 Joint Section 2, IGFS and GGOS Symposium "Gravity, Geoid and Height System 2024", September 4–6, Thessaloniki, Greece.
- Vergos, G.S., Natsiopoulos, D.A., Qirko, K., Balliu, O., Qershija, E., Ndoj, P., Tsokas, G., Stampolidis, A. (2024). Towards an improved gravimetric geoid in Albania. Presented at the GGHS2024 Joint Section 2, IGFS and GGOS Symposium "Gravity, Geoid and Height System 2024", September 4–6, Thessaloniki, Greece.
- Vergos, G.S., Sánchez, L., Barzaghi, R. (2024). The IHRF CC to ensure the long-term sustainability of the IHRS/IHRF. Presented at the GGHS2024 Joint Section 2, IGFS and GGOS Symposium "Gravity, Geoid and Height System 2024", September 4–6, Thessaloniki, Greece.
- Vergos, G.S., Sánchez, L., Barzaghi, R. (2024). Coordination center for the IHRF. Presented at the GGOS Days 2024 Symposium, October 10–11, Potsdam, Germany.
- Vergos, G.S., Sánchez, L., Barzaghi, R. (2024). Current activities of the newly established IAG/IGFS IHRF Coordination Center for the realization and maintenance of the IHRS/IHRF. Presented at the International Association of Geodesy Workshop on Asia Pacific Gravity, Geoid, and Vertical Datums 2024 Symposium, November 6–8, Manila, Philippines.
- Sánchez, L., Huang, J., Barzaghi, R., Vergos, G.S. (2021). Towards a Global Unified Physical Height System. Presented at the EGU General Assembly 2021, online, April 19–30, 2021. https://doi.org/10.5194/egusphere-egu21-1500.
- Sánchez, L., Huang, J., Barzaghi, R., Vergos, G.S. (2021). GGOS Focus Area Unified Height System: achievements and open challenges. Presented at the IAG Scientific Assembly 2021, online, June 28–July 2, 2021.
- Sánchez, L., and the IHRF Computation Team (2021). Status of the International Height Reference Frame (IHRF). Presented at the IAG Scientific Assembly 2021, online, June 28–July 2, 2021.

Dedicated Sessions during Conferences

During the reporting period, SC2.2 has participated in the organization of two related sessions in the GGHS 2024 "Gravity, Geoid and Height Systems 2024" Symposium and the forthcoming IAG Scientific Assembly in Rimini, Italy. GGHS2024 was held in Thessaloniki, Greece, from September 4-6, 2024 and a dedicated session, namely "Session 1: Reference systems and frames in Physical Geodesy" which attracted 24 presentations.

For the forthcoming 2025 IAG Scientific Assembly a session named "G02-1 Gravity Field and Reference Systems in Physical Geodesy" is planned, which has attracted 40 presentations. The session focuses on local, regional and global high-resolution geoid modelling, both in terms of developments in theory, processing methods, collocation with satellite, airborne, altimetry and shipborne data, etc. It includes contributions to solutions to various formulations of geodetic boundary-value problems with the aim of gravity field modelling on global, regional, and local scales. Additionally, the session focuses on the unification of the national height systems and gravity networks, the realization of the IHRF, possible refinements of standards and conventions for the definition and implementation of the height reference system, regional vertical datum and their unification, strategies for collocation of vertical reference stations with existing reference frames (GGOS core stations, ITRF, gravity stations, existing levelling networks, etc.) and studies on the temporal evolution of the IHRF.

Conference Organization and Planning

SC2.2 participates actively in the organization of the 2026 IGFS and Commission 2 Meeting, Gravity Geoid and Height Systems, which is planned for Fall 2026. Currently, the plan is to organize the conference in person in September 2026 in New Delhi, India.

JWG 2.2.1 Comprehensive Gravity Data Integration for the sub-cm Geoid/quasi-geoid Modelling

Chair: Ismael Foroughi (Canada)
Vice-Chair: Tao Jiang (China)

Meetings

The group held its first splinter meeting on September 6 during the Gravity, Geoid, and Height Systems 2024 conference in Thessaloniki. At this meeting, the group decided to work independently or jointly on the objectives of the working group. Along that two test datasets were presented which are available to all group members for research purposes:

Airborne vector gravity data

This dataset includes vector airborne gravity observations collected over part of the Colorado 1-cm geoid experiment, specifically between longitudes –106.6° and –105.6° and latitudes 36.8° to 37.8°N. The data were acquired at approximately 300–500 meters above ground level, following the terrain with a smooth drape flight pattern. Gravity was measured using the AIRGrav system, which includes three orthogonal accelerometers mounted on a gyro-stabilized platform to capture gravity in all three directions while reducing noise from horizontal motion. Aircraft position and velocity were determined using differential GNSS, further refined with Precise Point Positioning (PPP) for high positional accuracy. The data were collected to test the contributions of the horizontal components of the airborne gravity vector for geoid modelling.

Taiwan gravity dataset

This dataset includes land, airborne, shipborne, and satellite-derived gravity data, along with digital elevation models (DEMs) and GPS-levelling geoid heights, used for geoid modelling over Taiwan. Land gravity was measured from 1980 to 2006 using various gravimeters, with standard error estimates. Airborne gravity was collected in three campaigns (2004–2009) over Taiwan and nearby seas. Shipborne gravity surveys (2006–2013) near coastal areas used precise GPS positioning and filtering to achieve 500 m resolution and sub-2 mGal precision. Satellite altimetry filled offshore data gaps, providing 8 mGal precision using sea surface heights. DEMs and GPS-levelling data supported terrain corrections and hybrid geoid validation, with adjustments for vertical land motion to ensure consistency.

Awards

Dr. René Forsberg was awarded the prestigious EGU Vening-Meinesz Medal in April 2025 in recognition of his outstanding contributions to gravity field science. In his lecture "Gravity, Climate and Quantum" (Forsberg, 2025), he highlighted the evolving role of gravity measurements in achieving the long-sought goal of centimetre-level global geoid accuracy. He emphasized recent advances in satellite and airborne gravimetry, particularly over polar and mountainous regions, and the growing impact of gravity data on climate studies such as sea level rise and ice sheet mass loss. He also underscored the emerging potential of quantum sensing technologies for future geodetic and environmental applications.

Dr. Spiros Pagiatakis was awarded the CGU J-Tuzo Wilson Medal for his long-standing contribution to the field of Geodesy and Geomatics in Canada. Dr. Pagiatakis has been a key figure at York University. He helped to develop one of Canada's top Geomatics Engineering programs, shaping the future of many young scientists. His research has been groundbreaking, especially on GRACE satellite data, where he solved complex issues of satellite data stripes and gained international recognition.

Dr. Ropesh Goyal received the Indian Society of Geomatics "Prof. Kakani N Rao Young Achiever Award" for contributions in the domain of gravimetric and geometric geodesy with emphasis on geoid modelling and contributions towards Indian Geodetic Reference Frame, 2023.

Gravity datasets and software tools

Software

- FGrS (Fast Gravimetric Spherical Harmonic Synthesis)
  Software tool provided to perform high-performance computation of gravity field functional and it is Graphical User Interface for any system environment

Datasets

- Airborne Vector Gravity dataset
  This vector airborne gravity dataset over a 1-arc degree in Colorado, USA was collected using AIRGrav at 300–500m altitude. It includes all three gravity components and high-precision GNSS positioning, aimed at assessing the value of horizontal gravity data in geoid modelling.
- Taiwan Gravity Dataset
  The Taiwan gravity dataset combines land, airborne, shipborne, and satellite-derived gravity data with DEMs and GPS-levelling to support geoid modelling and validation, accounting for terrain and vertical land motion.

Projects

Precision Geoid Modelling and Method Integration in India

Dual National Projects on DEM-Based Modelling and Methodological Consensus covering objectives (a1, a2, b, c, d1, d3, e, f, g, k) of the group.
Contributor: Dr. Ropesh Goyal

- Funded by India's Department of Science & Technology, this project (2024–2027) develops DEM-integrated geoid models using rigorously consistent methods.
- A second national project (2025–2028), funded by Anusandhan National Research Foundation, explores harmonizing Stokes and Hotine-based formulations for consistent geoid determination using heterogeneous gravity data. Group-provided Taiwan data will be incorporated.

Continental Geoid Harmonization under NAPGD2022

Tri-national Collaboration on GEOID2022 for Canada, USA, and Mexico, covering objectives (a3, b, c, d1–d4, e, f, k, l) of the group.
Contributor: Dr. Ismael Foroughi

- As part of the North American-Pacific Geopotential Datum initiative, GEOID2022 integrates airborne, terrestrial, and satellite gravimetry across national borders to establish a unified high-accuracy geoid model.

Integrated Gravity Campaigns for Geoid Determination in Italy

National Aerogravity and Coastal Gravity Programs covering objectives (a1, a3, b, c, d1, d4, e, f, g, k) of the group.
Contributor: Dr. Riccardo Barzaghi

- The first project which started in September 2024 is ongoing. Data are collected along the entire shoreline of Italy. We'll be soon involved in the quality check of this data and in integrating them with the existing gravity database of Itlay.
- The second project is on an aerograv flight over the entire Italy. The kickoff meeting was two days ago and we are involved in the processing of the aerograv data, in the integration of these data with the existing ground/marine gravity data and in the estimation of a new geoid in the Central Mediterranean area.

SIRGAS-WGIII Leadership in Vertical Datum Modernization

Capacity Building, Guidelines, and Regional Geoid Models in South America, covering objectives (a1, a2, b, c, d1–d4, e, f, h, i, k, l) of the group.
Contributors: Dr. Ana Cristina Oliveira Cancoro de Matos and Dr. Gabriel Guimarães (Brazil)
The SIRGAS-WGIII (Vertical Datum) team has been actively involved in advancing geodetic knowledge and resources within the SIRGAS region. Their work in 2023 and 2024, alongside significant contributions to documentation and modelling, highlights their commitment to a robust vertical datum.
The team has played a key role in educational initiatives:

- 2023: They organized and participated in the 14th International School on "The Determination and Use of the Geoid" held in Buenos Aires, Argentina. This school provided crucial training on geoid determination and its practical applications. More details can be found at https://sirgas.ipgh.org/capacitaciones-2023-es/xiv-escuela-internacional-sobre-la-determinacion-y-uso-del-geoide/
- 2024: The team also participated in the SIRGAS 2024 Symposium in Bogotá, Colombia, a major event that discussed advancements and challenges in SIRGAS activities related to gravity and geoid modeling. Information about the symposium is available at https://sirgas.ipgh.org/simposio-2024-2/

This edition of the SIRGAS Symposium was organized jointly with the Agustín Codazzi Geographic Institute and with the support of the Pan-American Institute of Geography and History (PAIGH) and the International Geodesy Association (IAG).

The SIRGAS-WGIII team has contributed to developing and disseminating vital technical guidelines, available on the SIRGAS website: https://sirgas.ipgh.org/recursos/guias/

These include:

- "Directrices para El Cálculo De Los Valores de Potencial de Gravedad en las Estaciones IHRF de la Region SIRGAS" (Guidelines for the Calculation of Gravity Potential Values at IHRF Stations in the SIRGAS Region). This document outlines standardized procedures for calculating gravity potential, which is essential for establishing a consistent vertical datum.
- "Directrices para trabajo de campo y procesamiento de mediciones gravimétricas" (Guidelines for field work and gravimetric measurements processing). This manual provides practical guidance for obtaining accurate and reliable gravity measurements, which are essential for geoid modeling and the realization of vertical datums.

A significant achievement of SIRGAS, with contributions from WGIII, is the provision of new geoid and quasi-geoid models for the South American community (SAM_GEOID2023 and SAM_QGEOID2023). These models are a fundamental component in the precise determination of height and various geodetic applications across the continent. It can be downloaded from the International Service for the Geoid (ISG) website: https://www.isgeoid.polimi.it/Geoid/America/Southamerica/southamerica2023_g.html

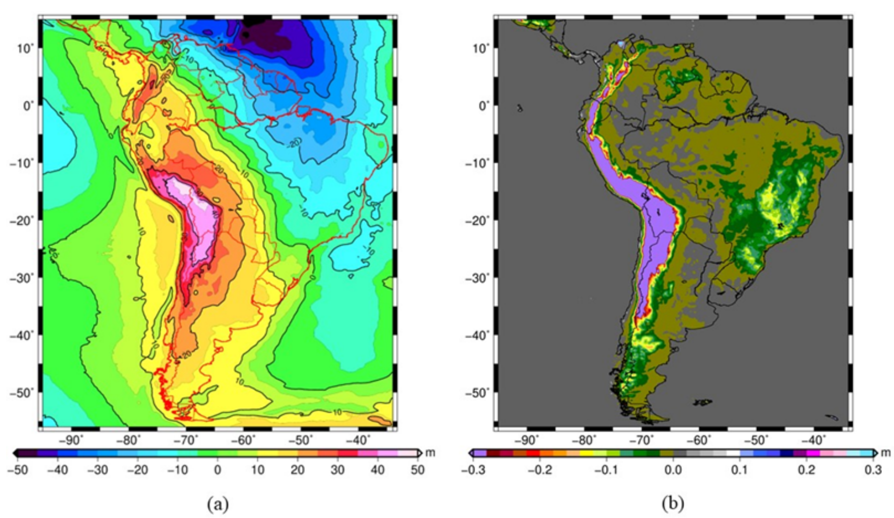

Fig. 2. The South American geoid model 2023 (SAM_GEOID2023). (b) difference between the geoid (SAM_GEOID2023) and the quasi-geoid (SAM_QGEOID2023) models

Coastal Geoid and Sea Level Monitoring in Norway

High-Resolution Geoid Modelling for Sustainable Coastal Development covering objectives (a2, c, d1, d4, e, k) of the group
Contributor: Matea Tomić (PhD Candidate), Norwegian University of Life Sciences

- Focuses on geoid modelling for the Norwegian coastline using marine gravity, bathymetry, and GNSS/levelling integration. Final results are expected in 2025 as part of her PhD thesis.

Adaptive Covariance and Terrain-Aware Geoid Modelling in Iran

Patch-Wise Least Squares Collocation with Optimized Covariance Estimation, covering objectives (a1, f, g, k, j) of the group.
Contributor: Sabah Ramouz (PhD Candidate), University of Tehran

- Builds on the Covariance Estimation by Cross-Validation (CEC) framework. Focuses on anisotropic, terrain- and geology-aware gravity field modelling for enhanced geoid accuracy.

Contributions from Journal Articles

Overarching Summary

The collected body of work by IAG Working Group 2.2.1 members represents a comprehensive and multifaceted contribution toward high-accuracy regional geoid/quasigeoid modelling. These papers collectively explore the integration of diverse gravity data sources, terrestrial, airborne, marine, and satellite, along with topographic, GNSS/levelling, and atmospheric corrections. The studies cover both theoretical advancements and practical applications, focusing on error modelling, data fusion, topographic and atmospheric corrections, and machine learning integration. Collectively, they drive the field closer to the goal of sub-centimetre geoid determination through innovative methodology, software development, and targeted regional case studies.

Objectives Addressed

a) **Land-level gravity observations**
(Abbak et al., 2025; Alves Costa et al., 2023; Cob et al., 2022; Čunderlík et al., 2023; Eshagh, Pitoniak, & Novák, 2025; Foroughi et al., 2023; Hwang, 2023, 2024; Jiang et al., 2025; Jensen et al., 2025; Kamali et al., in preparation; MTech Thesis, 2025; Nsiah Ababio et al., 2024; Pitoniak et al., 2025; Ramouz & Safari, 2020; Šprlák & Pitoniak, 2024; Udama et al., 2024; Vu et al., 2024)

b) **Combination of scalar and vector gravity observations**
(Alves Costa et al., 2023; Foroughi et al., 2024; Goli & Foroughi, 2025; Jensen et al., 2025; Pitoniak et al., 2023; Udama et al., 2024; Vu et al., 2024)

c) **Satellite gravity models and integration with high-frequency gravity data**
(Cob et al., 2022; Eshagh et al., 2024; Goli & Foroughi, 2025; Goyal et al., 2023;

Guimarães et al., 2024; Inoue & Guimarães, 2025; Odera et al., 2024; Pitoniak et al., 2023; Pham et al., 2023)

d) Geoid error evaluation
(Abbak et al., 2025; Eshagh, Pitoniak, & Novák, 2025; Foroughi et al., 2023; Gerlach & Rummel, 2024; Goyal et al., 2023; Hwang, 2023; Jiang et al., 2025; Marotta et al., 2024; Novák et al., 2024; Nsiah Ababio et al., 2024; Pitoniak et al., 2025; Pham et al., 2023; Ribeiro et al., 2023; Šprlák & Pitoniak, 2024; Tenzer & Novák, 2025; Trojanowicz et al., 2024a, 2024b; Udama et al., 2024)

e) Use of GNSS/levelling
(Abbak et al., 2025; Čunderlík et al., 2023; Gerlach & Rummel, 2024; Goyal et al., 2023; Guimarães et al., 2024; Hwang, 2024; Inoue & Guimarães, 2025; Jiang et al., 2025; Nsiah Ababio et al., 2024; Odera et al., 2024; Pitoniak et al., 2023; Ribeiro et al., 2023; Tenzer & Novák, 2025)

f) Topographic corrections
(Alves Costa et al., 2023; Foroughi et al., 2023; Hwang, 2023; Marotta et al., 2024; Tenzer & Novák, 2025)

g) Complexity of data & interpolation/downward continuation
(Foroughi et al., 2023; Goyal et al., 2023; Kamali et al., in preparation; Novák et al., 2024; Ramouz & Safari, 2020)

h) Synthetic ultra-high degree models
(Alves Costa et al., 2023; Goli & Foroughi, 2025)

i) Experimental data & software tools
(Goli & Foroughi, 2025; Pitoniak et al., 2025; Šprlák & Pitoniak, 2024)

j) AI and ML applications
(Jensen et al., 2025; Jiang et al., 2025)

k) Comprehensive strategy reports
(Referenced throughout; contributions from nearly all studies)

i) Presentations
(28th IUGG, EGU 2024, GGHS 2024, SIRGAS meetings, XIII Colóquio Brasileiro de Ciências Geodésicas, Slovak-Polish-Czech Geodetic Events, Satellite Methods in Theory and Practice Conference, AGU 2023 and 2024).

Summary of Articles

Pitoňák et al. (2023a) validated GOCE space-wise gravitational gradient grids by transforming them into height anomalies using a spectral combination method and comparing them with GNSS/levelling data over Czechia/Slovakia and Norway. Their method allows downward continuation without matrix inversion and includes error estimation, residual terrain modelling, and spectral weighting. The study demonstrated significant accuracy improvements across GOCE data releases and supports efficient integration of satellite and surface gravity data.

Pitoňák et al. (2023b) applied a spectral combination method to estimate height anomalies from satellite-measured gravitational potential gradients. The method solves over-determined geodetic boundary-value problems by combining gradients (up to third order) using spectral weights that minimize global mean-square error. Closed-loop tests using synthesized gradients from a global model showed horizontal derivatives contribute more significantly to the solution than vertical ones. This study supports the efficient integration of various satellite gravity observables for improved gravity field recovery.

Satellite gravimetry plays a central role in observing Earth's gravity field and its temporal changes, providing key insights into mass redistribution and internal dynamics. Eshagh et al. (2024) offer a comprehensive review of how various satellite observables, such as orbital perturbations, range rates, and gravitational gradients, relate to spherical harmonic coefficients that define global gravitational models. They discuss the use of these models in geoid and height determination, as well as in a broad range of Earth science applications, including crustal thickness, ocean currents, and glacial isostatic adjustment. The paper also explores future developments in satellite gravimetry, supporting objective-driven geoid modelling and integration of multi-source data.

Foroughi et al. (2023) reviewed and developed methods to formally estimate the internal error of regional geoid models, aiming for sub-centimetre accuracy. Using the one-step integration method in Helmert space, they analyzed how errors from global gravity models (EGMs), digital terrain models (DTMs), and gravity observations propagate into the final geoid solution. Applying this in Colorado, they found that observation design, especially the quality and distribution of airborne and ground gravity data, is the largest contributor to total geoid error. They showed that using airborne gravity with a gentle drape at 300–500 m altitude and improved DTM quality enables geoid modelling with internal errors below 1 cm.

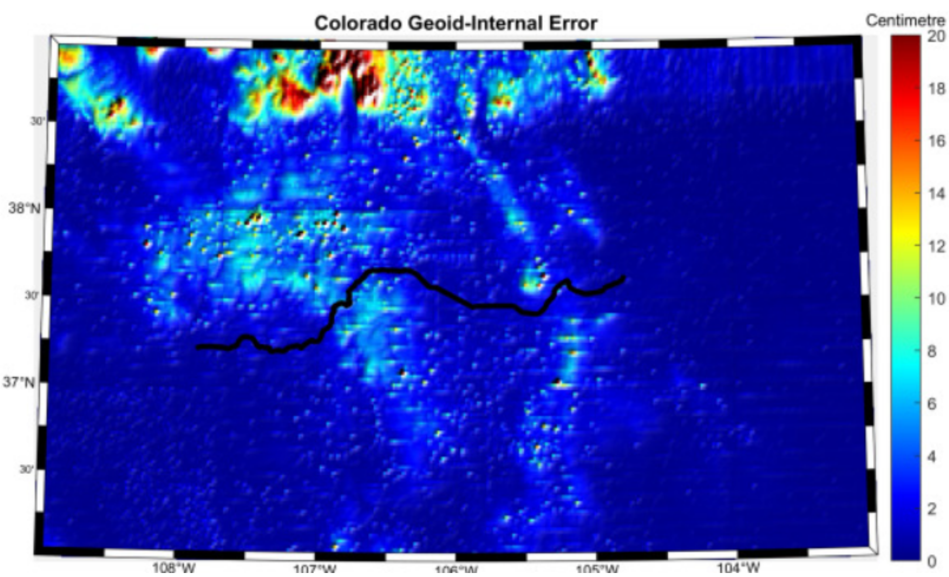

Fig. 3. Total error estimate of the geoid heights in the Colorado region (Foroughi et al., 2023)

Novák et al. (2024) explore how integral-based solutions to geodetic boundary-value problems can be accompanied by stochastic models to quantify uncertainties. The paper emphasizes that while deterministic models estimate unknown gravitational field parameters, incorporating observational errors through stochastic models enables the calculation of error variances and covariances. This dual approach helps evaluate the model quality and data reliability, which is crucial for reliable geoid determination and gravity field modelling using noisy or diverse datasets.

Tenzer and Novák (2025) address inconsistencies between gravimetric geoid models and Helmert's orthometric heights, which arise from oversimplified gravity approximations within topographic masses. While regional geoid models achieve centimetre-level accuracy, Helmert heights can be off by meters in mountainous regions due to assumptions of constant density and simplified gravity reductions. The authors propose a unified computational scheme that modifies geoid modelling methods to also produce consistent and accurate orthometric heights, enabling both to be computed simultaneously.

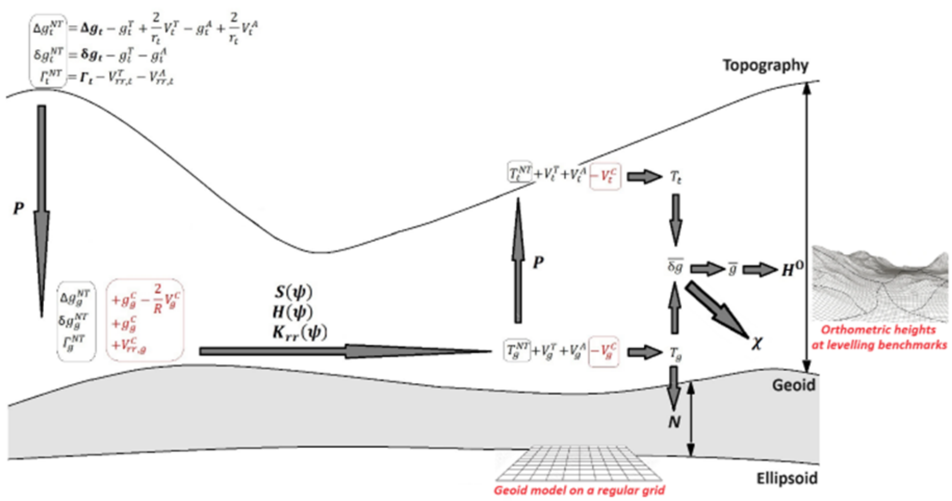

Fig. 4. Optimal design of the computational scheme for consistent determination of the geoid height and orthometric height (Tenzer and Novak, 2025)

Odera et al. (2024) demonstrate how tailored gravity-field models, built by combining global gravity models, topographic residual gravity, and terrestrial gravity observations, can effectively reproduce local gravity and quasigeoid heights in data-sparse regions like Cameroon and South Africa. Their models, validated against independent GPS/levelling data, achieve accuracy comparable to national quasigeoid models. The study highlights the usefulness of regional data combination strategies and validation using GNSS/levelling, especially where terrestrial data is sparse.

Airborne gravity data collected using the GIRAFE cold-atom gravimeter has shown significant potential to enhance quasigeoid modelling in coastal regions where gravity data are sparse or inconsistent. Over the Bay of Biscay, the GIRAFE dataset outperformed older shipborne data and provided up to a 50% improvement in quasigeoid accuracy near the coast. When merged with refined gravity data, it achieved ∼1cm accuracy, closely aligning with the sub-centimetre goal of modern geoid models. These results confirm the value of quantum sensors in gravity field recovery (Vu et al., 2024).

Jensen et al. (2025) present airborne gravity data from Iceland and Greenland collected using both a cold-atom quantum gravimeter and a classical strap-down system. With accuracy ranging from 1–2mGal, the dataset highlights the similar performance of both sensors while revealing distinct error behaviours. The study suggests that combining quantum and classical data could enhance overall gravity field recovery.

Cob et al. (2022) introduced PMGVD2022, an epoch-based height reference system for Peninsular Malaysia, replacing the outdated PMGVD2000. By incorporating over 30 years of tide gauge records, vertical land motion trends, and a new gravimetric geoid fitted to local mean sea level, the system enables consistent and accurate GNSS-based orthometric height determination. This improves the reliability of sea level rise and flood risk assessments along coastal regions.

Nsiah Ababio et al. (2024) revisited the levelling network and compiled a new geoid model as part of modernizing Hong Kong's vertical datum. They highlighted significant discrepancies in geoid-to-quasigeoid separation when comparing traditional planar Bouguer-based methods to more accurate numerical models. By incorporating a digital rock density model, they quantified the impact of anomalous topographic density, showing deviations up to 1.6cm. Their findings emphasize the need for precise conversion methods between geoid and quasigeoid, even in moderately elevated regions.

Nsiah Ababio and Tenzer (2024) compiled a digital rock density model for the Hong Kong territories using geological maps and published density data. Their analysis showed that local rock densities range from 2101 to 2681kg·m^{-3}, generally lower than the commonly used average of 2670kg·m^{-3}. This reflects the dominance of light volcanic and sedimentary formations, with minimal presence of denser metamorphic rocks. The resulting density model is crucial for improving the accuracy of detailed geoid models and orthometric heights.

Tenzer and Nsiah Ababio (2023) provide theoretical and numerical validation that the classical approach to geoid-to-quasigeoid separation, based on the planar Bouguer anomaly, is consistent with Helmert's definition of orthometric heights. Their analysis confirms that differences between normal and orthometric corrections closely match the geoid-to-quasigeoid separation, with variations generally within ±1mm. Minor discrepancies observed in Hong Kong levelling data were attributed to levelling errors rather than model inconsistencies. This reinforces the internal consistency of classical height system definitions.

Čunderlík et al. (2023) present results from the modernization of the Hong Kong Principal Datum (HKPD) through new gravity and precise levelling observations. A detailed gravimetric quasigeoid model was developed using a finite-element solution to the geodetic boundary-value problem, accounting for oblique derivatives directly on the topographic surface. The resulting model showed strong agreement with the geometric quasigeoid from GNSS-levelling, with a standard deviation of ±3.3cm, aligning well with measurement accuracy expectations.

Eshagh, Pitoňák, and Novák (2025) investigate four techniques for estimating surface gravity anomalies from GOCE satellite gravity gradient data using a discretized Fredholm integral model over Central Europe. These techniques, direct inversion, remove-compute-restore, truncation reduction, and a modified integral inversion, are analyzed under Tikhonov regularisation due to the ill-conditioned nature of the problem. The study also introduces models to estimate biased and de-biased variance-covariance matrices. Results suggest that the remove-compute-restore method yields a lower signal-to-noise ratio, requiring stronger regularisation, which can result in an underestimation of uncertainty.

This study by Pitoňák et al. (2025) introduces a MATLAB-based software library for computing far-zone effects in integral transformations of gravitational potential gradients up to the third order. It addresses the challenge of limited global data coverage by numerically evaluating far-zone contributions, which are critical for accurate geoid and quasigeoid modelling. The library includes tools to calculate integral kernels, error kernels, and truncation coefficients, and implements closed-loop tests to validate its accuracy.

Šprlák and Pitoňák (2024) provide a comprehensive theoretical review and numerical validation of far-zone effects in spherical integral transformations used in gravitational field modelling. They focus on decomposing global integrals into near- and far-zone contributions, with the latter approximated using harmonic expansions. Their work supports the accurate evaluation of various gravitational potential functionals and implements the formulations in a MATLAB package validated through closed-loop tests.

An MTech thesis completed at the Department of Civil Engineering, IIT (BHU) in May 2025 focused on evaluating and optimizing various techniques for gridding gravity anomalies to support accurate geoid modelling. The study developed and tested interpolation methods including Least Squares Collocation, Kriging, Spline, Nearest Neighbor, and machine learning models like Random Forest and XGBoost. These were assessed across different terrains using standard error metrics to determine the most effective technique for generating consistent and precise gravity grids. The work has been accepted for presentation at the IAG Scientific Assembly 2025.

Abbak et al. (2025) evaluate the effects of different deterministic modifications of the Stokes kernel (Wong-Gore, Vaníček-Kleusberg, and Featherstone-Evans-Olliver) and two terrain correction approaches (mass-prism and mass-cylinder based) on precise geoid modelling using the Stokes-Helmert method in a mountainous region of Türkiye. Using two satellite-only GGMs and validating against GNSS/levelling data, the study finds that although multiple combinations yield similar overall statistics, notable local differences emerge that are critical for achieving centimetre-level geoid accuracy.

Jiang et al (2025) present a physics-informed neural network (PINN) framework that integrates physical laws, such as Laplace's equation, into a deep learning model for regional geoid modelling. Using terrestrial and airborne gravity data from the Colorado 1cm experiment, the PINN model outperformed traditional methods and a data-driven neural network (DDN), achieving a standard deviation of 2.1cm compared to GSVS17 GNSS/levelling benchmarks, up to 27.6% more accurate than DDN. This method demonstrates excellent generalization even under sparse data, capturing both global and local geoid features and offering a robust, interpretable approach for future geodetic applications.

Alves Costa et al. (2023) present the recent advances and future directions of the SIRGAS initiative, aimed at establishing a unified regional geodetic reference frame for the Americas. The geometric component is maintained via a network of 500 GNSS stations processed by ten analysis centers and aligned with ITRF. For physical heights, SIRGAS contributes to densifying the International Height Reference Frame (IHRF), relying on high-resolution gravity modelling and geoid determination. Efforts are also underway to develop a regional densification of the International Terrestrial Gravity Reference Frame (ITGRF), by assessing and expanding the network of absolute gravity stations. Capacity building and national adoption of the frame are additional core goals.

Guimarães et al. (2024) presented a combination of a regional gravity field model (via the Remove–Compute–Restore method) and GNSS/levelling observations were used to estimate the vertical offsets between Brazil's local vertical datums (Imbituba and Santana) and the global vertical datum under the IHRF framework. The resulting geopotential numbers and vertical offsets quantify significant differences between the two local datums and underscore the importance of accurate gravity field modelling for global height unification.

Inoue and Guimarães (2025) review the historical development and current status of height systems across the Americas, emphasizing South America's progress toward integration into the International Height Reference Frame (IHRF). The paper outlines the efforts of Working Group III of SIRGAS over the past 25 years, presents a bibliometric analysis of scientific contributions, and compares global geopotential models with a regional gravity model at 17 Latin American IHRF stations. Results underscore the need for gravity data densification in the Andes and the improvement of global models to ensure reliable vertical referencing.

Marotta et al. (2024) investigate how various parameters impact the determination of gravimetric geoid models using the remove-compute-restore (RCR) technique, with a focus on the São Paulo region in Brazil. The study assesses the effects of global geopotential model choice, Stokes kernel modifications, topographic model resolution, and mass density values on geoid accuracy. Results indicate that Stokes kernel modifications and the selected geopotential model significantly affect geoid height estimates, while variations in digital terrain model resolution and lateral density have a lesser effect. This highlights the need for careful data and parameter selection to ensure consistent geoid determination.

Ribeiro, Guimarães, and Marotta (2023) assess how integrating shipborne marine gravity data with global satellite-derived marine gravity models (DTU17 and GRAV31.1) affects the computation of geopotential values at coastal IHRF stations in Brazil (CEFT and IMBT). While the IHRF mandates geopotential numbers and homogeneous gravity coverage around stations, the study finds that adding high-frequency marine gravity data did not improve the accuracy of the computed gravity potential at these coastal sites. This highlights challenges in offshore gravity data integration and the limited utility of high-frequency marine gravity in such contexts.

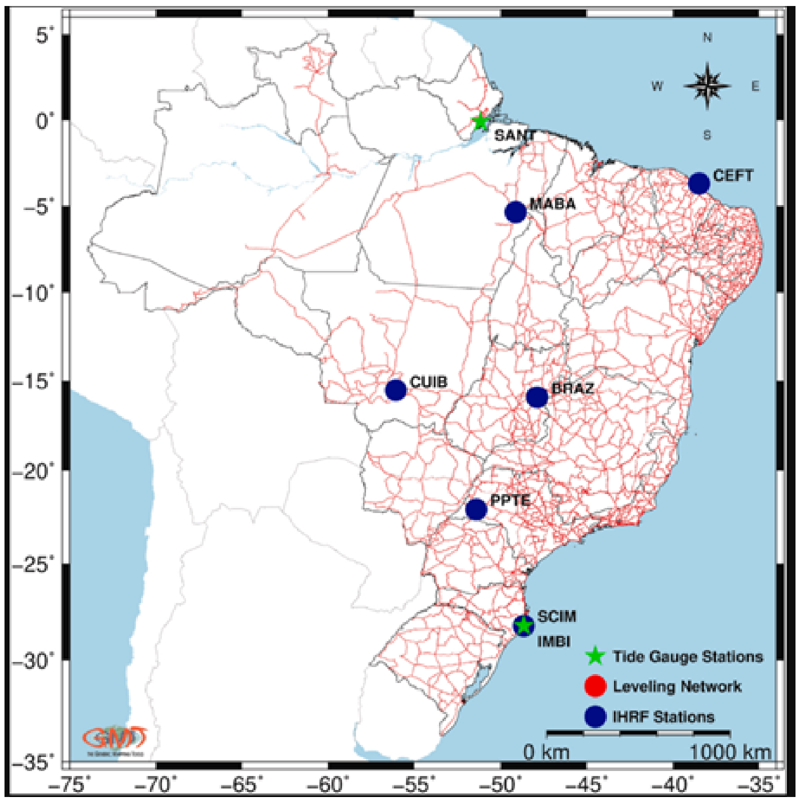

Fig. 5. Brazilian leveling network (red), local vertical data (tide gauges in green), and IHRF stations (Guimarães et al. (2024))

Building on Ramouz et al. (2020), the Improved Covariance (IC) method enhances local gravity field modelling using Least Squares Collocation (LSC) with the Tscherning-Rapp (TR74) covariance function. Ramouz and Safari (2020) applied the IC method to geoid modelling in Tehran, showing a 25% improvement in accuracy over GNSS/levelling data. Unlike traditional approaches that fit a theoretical covariance model under isotropy and stationarity assumptions, IC searches the parameter space to minimize LSC cross-validation errors. Kamali et al. (2025 in prep.) expanded this approach by incorporating anisotropic covariance estimation using the Covariance Estimation by Cross-Validation (CEC) algorithm and patch-wise LSC for spatially adaptive modelling.

Studies on error propagation of classical gravity field modelling techniques (e.g., Ophaug V, Gerlach C (2020) Error propagation in regional geoid computation using spherical splines, least-squares collocation, and Stokes's formula. J Geod 94(12):120) typically result in error estimates of geoid heights and geoid height differences which show that potential differences from classical levelling could still be competitive over short to medium distances. Gerlach and Rummel (2024) posed the question, of whether gravity field modelling could benefit from the exploitation of classical levelling. A study based on synthetic data (test case of the UELN-network in central Europe) was performed, whereby two scenarios were investigated: (i) potential differences from levelling and an existing geoid model are combined in a common network adjustment leading to potential values at the benchmarks of the levelling network and (ii) potential differences from geodetic levelling are used as additional observable for regional gravity field modelling, leading to a grid of geoid heights based on classical observables like gravity anomalies and now also on levelled potential differences. It was shown that incorporating levelled potential differences (i) improves the quality of a continent-wide network of GNSS-heights by about 40% and (ii) that formal and empirical errors of a regional geoid model are reduced by about 20% at levelling benchmarks. Even though these numbers strongly depend on the stochastic model, the study shows that, in general, there is the benefit of incorporating levelling data in regional geoid modelling and it is pointed out that the methods provide data products that are consistent with the different data sets within their error bounds (no discrepancies between national levelling networks and geoid-based vertical reference frames). The method cannot only be applied to classical spirit leveling be also to chronometric or hydrodynamic leveling.

The determination of the geoid–quasigeoid separation (GQS) is most often based on the use of Bouguer gravity anomalies or disturbances with additional corrections. A different approach to the problem of determination of the GQS values, based on the geophysical gravity inversion technique (GGI approach) was proposed by Trojanowicz et al. (2024a). The authors presented details of the solution and the first results of tests performed in the area of the Colorado 1 cm geoid computation experiment. The analyses carried out showed a significant effect of changes in the density of topographic masses on both GQS values and geoid heights determined by the GGI approach. The determined GQS values were compared with the reference values determined previously using the complete classical approach, assuming the same topographic mass densities. The differences between the compared values were small, with the maximum differences reaching 0.075 m and a standard deviation of 0.007 m.

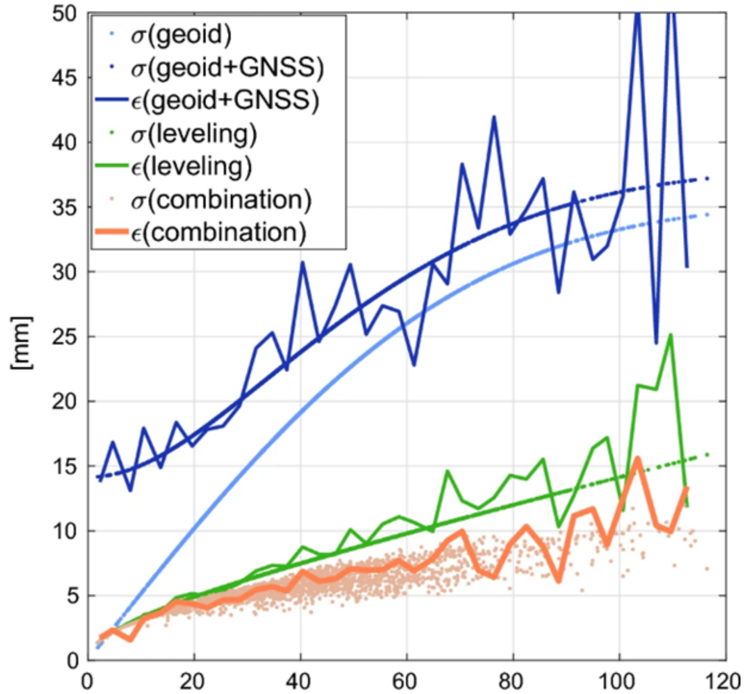

Fig. 6. Errors of height differences from different realizations of the vertical reference frame as functions of the point distance (=length of levelling line). Different realizations are GNSS-leveling (bluish colors), geodetic levelling (green) and their combination (reddish colors) (Gerlach, and Rummel, 2024)

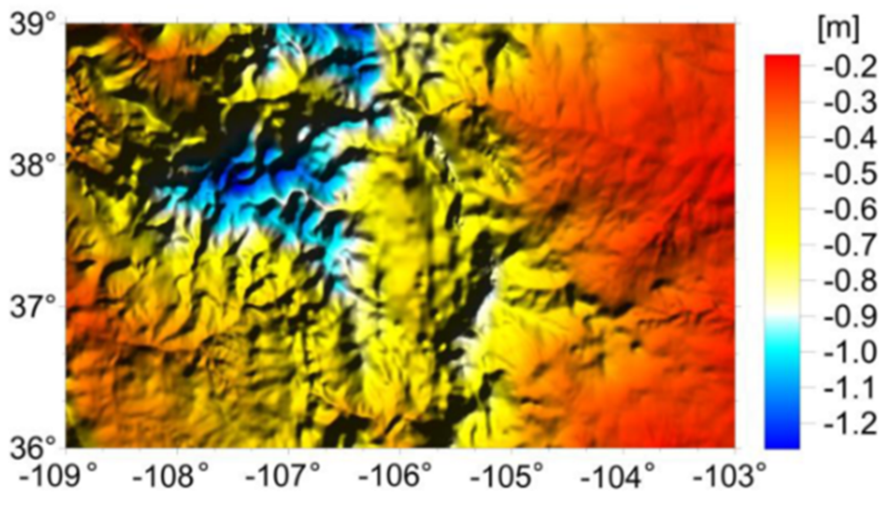

Fig. 7. Geoid to quasigeoid separation in Colorado (Trojanowicz et al. (2024a))

Trojanowicz et al. (2024b), considering topography as the lower limit of the atmosphere, determined and analyzed the components of atmospheric gravity correction for the area of Poland. The authors used a model of atmospheric density based on the United States Standard Atmosphere 1976 model and algorithms typical for the determination of topographic gravity reduction. The topography-bounded gravity atmospheric correction values in the elaboration area range from 0.748 to 0.886 mGal. The determined correction values were different from standard, approximate atmospheric correction values (based on the International Association of Geodesy approach) in the range of 0.011 mGal for points at sea level up to 0.105 mGal for points located at an altitude of approximately 2600 m. The values of the correction were also strongly correlated with the heights of the points and also depended on the surrounding relief. The results obtained confirm previous studies on the computation of atmospheric gravity corrections.

Udama et al. (2024) developed a gravimetric geoid model over Bali by combining satellite (GOCO06S, GGMplus), airborne (at $\tilde{4}$100m altitude), and terrestrial gravity data using Least Squares Collocation (LSC) and Remove-Compute-Restore (RCR) techniques. The resulting model was validated against a geometric geoid derived from GNSS/levelling. A standard deviation of 14.46cm was achieved with satellite and airborne data alone, and 16.37cm when terrestrial data were included. For comparison, GOCO06S and INAGEOIDV2 geoid models had standard deviations of 79.56cm and 16.40cm, respectively. The results demonstrate improved resolution and accuracy, though the reliability of validation was impacted by errors in the GNSS/levelling dataset. The study underscores the importance of high-frequency gravity signals near the Earth's surface and highlights the need for improved geometric reference data in Indonesia.

Goyal et al. (2023) investigated the consistency of geoid models across India by comparing three widely used computation methods developed at Curtin University of Technology (CUT), the University of New Brunswick (UNB), and the Royal Institute of Technology (KTH). Although GNSS/levelling validation showed that each method performed well locally (STD within ±0.01m, with some exceptions), the inter-model comparison revealed significant discrepancies, up to 5m in some regions, highlighting regional inconsistencies. This suggests that using a single geoid computation method nationwide may not yield uniformly precise results. The authors advocate for a merged approach that integrates regionally optimized models to develop a more consistent and accurate national geoid surface.

Pham et al. (2023) assessed the performance of several high-degree Global Geopotential Models (GGMs) over Vietnam by comparing them to GNSS/levelling data. The study found that XGM2019e_2159 had the best absolute and relative accuracy, followed by EIGEN-6C4, GECO, SGG-UGM-1, SGG-UGM-2, and GGMPlus, while EGM2008 performed the worst. Notably, relative model performance was largely unaffected by terrain or location. For baselines over 20km, XGM2019e_2159 showed up to 40% better accuracy than EGM2008. After fitting, all models exhibited comparable relative accuracies, but EGM2008 continued to show significant regional inconsistencies. These results support more informed GGM selection and contribute to the development of consistent quasigeoid models in Vietnam.

Dr. Cheinway Hwang has been working on two studies closely aligned with the objectives of our working group. The first study focuses on improving terrain corrections (TCs) in Taiwan using high-resolution LiDAR-derived DEMs (1 m to 20 m) and a spatially varying density model. This work enhances the accuracy of topographic corrections required for precise geoid modelling in rugged and coastal regions like Taiwan.

The second study addresses the quality and consistency of observed geoidal heights from GNSS/levelling in Taiwan in 2023. We identified significant challenges arising from temporal mismatches, vertical ground motions, and discrepancies in geodetic reference frames. By applying systematic outlier detection and cluster-based error analysis, we refined over 1,700 GNSS/levelling points for improved hybrid geoid construction. These efforts contribute to reducing errors in GNSS-based height transformation and to validating gravimetric geoid models.

Dr. Ilya Oshchepkov is currently developing atmospheric corrections for gravity-related quantities to ensure alignment with the gravity definition used in the International Terrestrial Gravity Reference Frame (ITGRF). This work, initiated under the GGOS Working Group on new normal gravity field parameters, directly supports the objectives of JWG 2.2.1 on integrating gravity data for sub-centimetre geoid/quasi-geoid modelling. Initial results will be presented at the IAG Scientific Assembly in Rimini.

Goli and Foroughi (2025) introduce FGrS (Fast Gravimetric Spherical Harmonic Synthesis), a software tool designed for high-performance computation of gravity field functionals using ultra-high-degree global geopotential models (GGMs). Available in both open-source and GUI formats, FGrS employs the Belikov method for evaluating fnALFs and supports parallelized computations over regular grids, varied-height grids, and scattered points. A novel interpolation approach for varied-height grids significantly improves speed and accuracy, achieving very low relative errors even in mountainous areas like the Himalayas. FGrS calculates various gravity-related quantities, such as potential, gravity anomalies, and geoid heights, and outperforms existing tools in terms of both speed and precision.

Foroughi et al. (2024) demonstrate that the horizontal components of the airborne gravity vector, representing deflections of the vertical, can be effectively used in geoid modelling to optimize flight line spacing. Using a one-step integration method and solving the boundary value problem via weighted least-squares, they show that including horizontal gravity components allows for a 40% increase in flight line spacing without sacrificing geoid accuracy. This result, tested over Colorado, suggests significant cost savings in airborne surveys.

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5 SC 2.3 Gravity Missions

Chair: David Wiese (United States of America)
Vice-Chair: João de Teixeira da Encarnacao (Netherlands)

Overview

SC2.3 promoted and stimulated activities that provided a scientific environment for the development of the next generation of static and temporal gravity field solutions. This included fostering exchanges among data processing entities, focusing on the optimum combination of satellite gravimetry data with complementary data types, and emphasizing functional and stochastic models in gravity field processing. Additionally, SC2.3 stimulated communication with gravity field model user communities (climatology, oceanography/altimetry, glaciology, solid Earth physics, hydrology, etc.) as well as relevant IAG organizations. Finally, SC2.3 contributed to the identification and definition of enabling technologies for future gravity field missions, as well as the promotion of existing and planned gravity field missions and technology demonstrations that are currently in development, supporting their implementation.

Gravity-based data services for the Copernicus Climate Change Service

In early 2023, the EU research project Global Gravity-based Groundwater Product (G3P; www.g3p.eu) under the leadership of the GFZ Helmholtz Centre for Geosciences (GFZ) concluded after more than three years of project runtime. As a major deliverable, the prototype of a data service for a global product on groundwater storage variations was provided. The G3P processing chain follows a data combination approach of Terrestrial Water Storage (TWS) variations from GRACE and GRACE-FO with global data products of soil moisture, snow water equivalent, glacier mass change, and surface water storage to isolate groundwater storage. The compartmental storage data sets are based on (i) observations (mainly satellites) as far as possible, and (ii) existing data services that are operational in the Copernicus portfolio and have been extended and adapted for G3P. The development continued over the last two years, with the latest version of the G3P prototype (V1.12) being produced in 2024.

Starting at the end of 2024, the G3P prototype is now being developed by GFZ into a full operational service for the Copernicus Climate Change Service (C3S) through a service contract with Copernicus/ECMWF. In this framework, two new Essential Climate Variable (ECV) data products and services will be added to the Land Hydrology Domain of C3S. These cover the ECV quantities Terrestrial water storage anomalies (TWSA) and Groundwater storage change (GWSC). For both products, the underlying time-variable gravity field models are provided by IAG's International Combination Service for Time-variable Gravity Fields (COST-G) Service. The subtraction approach from TWSA to the residual GWSC is outlined in Figure 8, together with the main institutions that provide the individual compartmental storage data sets for this approach. The first Climate Data Record (CDR) on TWSA, together with the

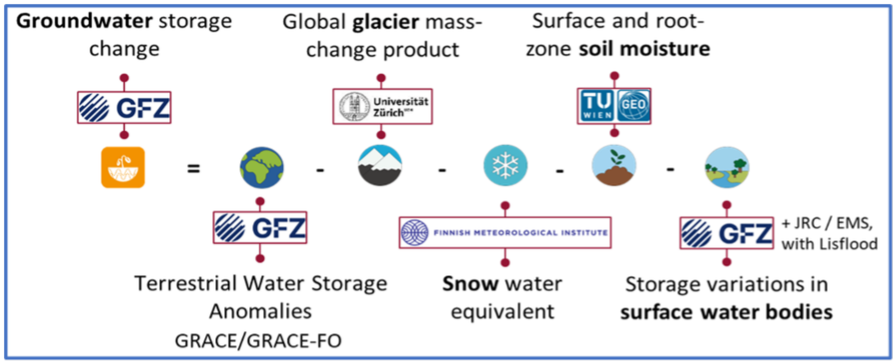


Fig. 8. Scheme of the data combination approach that is set up for the operational data service of the ECV quantity Groundwater Storage Change developed for the Copernicus Climate Change Service C3S.

relevant documentation documents following the C3S standards, is being provided to Copernicus in June 2025.

GRACE and GRACE-FO

The NASA/GFZ GRACE-FO satellites continued successful operation, adding to a now 23-year climate data record of Earth system mass change. In September 2024, a new RL06.3 gravity solution was released for the GRACE-FO mission, marking significant improvements in solution quality for the last two years of mission operations. The advance in RL06.3 focused on the development of a new functional model for the accelerometer data processing.

GRACE-Continuity (GRACE-C)

NASA and DLR signed an implementing arrangement to realize a successor mission, called GRACE-Continuity (GRACE-C), to the currently operational GRACE-FO mission. GRACE-C is scheduled to launch in December 2028 and represents the merger of the previous Mass Change (US) and GRACE-I (Germany) concepts that had been studied as possible successor mission concepts.

In the last two years, GRACE-C successfully passed Mission Design Review in July 2023, Preliminary Design Review in March 2024, and Critical Design Review in May 2025, and is currently in Phase C of development. The GRACE-C mission relies significantly on heritage from GRACE-FO; the primary change is that the Laser Ranging Interferometer (LRI) takes the place of the Microwave Ranging Instrument (MWI) as the primary ranging instrument. The LRI on GRACE-C is taking advantage of the successful technology demonstration on GRACE-FO, but is being upgraded to be fully redundant on GRACE-C. Other notable changes in the spacecraft design relative to GRACE-FO include flying a GNSS receiver that will track both the GPS and Galileo constellations, and using low-shock thrusters to reduce disturbances imparted to the spacecraft during routine Attitude and Orbit Control System (AOCS) operations. GRACE-C is planned to be launched in a polar orbit at approximately 500 km altitude.

Next Generation Gravity Mission (NGGM)

ESA continued development of the Next Generation Gravity Mission (NGGM) in Phase B1 over the last two years. The focus has been on instrument procurement and technology and concept maturation. NGGM employs a similar measurement concept as GRACE-C, consisting of a pair of satellites separated in the along-track direction, tracking intersatellite distance changes precisely with a laser interferometer to measure Earth's gravitational changes. NGGM will differ from GRACE-C by flying in a lower, controlled inclined orbit. It will also employ ultra-sensitive electrostatic accelerometers and a drag compensation system to maintain a roughly constant altitude throughout the mission and ensure accurate inter-satellite pointing. NGGM is planned to launch in 2032, into a 400 km altitude orbit at 70 degree inclination. NGGM, when combined with GRACE-C observations, aims to extend and improve Earth system mass change measurements by providing enhanced spatial (170km) and temporal (sub-weekly) resolution time-varying gravity field products with reduced uncertainty and latency to address the international user needs and demonstrate operational capabilities relevant for Copernicus.

Mass Change and Geosciences International Constellation (MAGIC)

Mass Change and Geosciences International Constellation (MAGIC) is the ESA-NASA concept for collaboration on future satellite gravity observations. MAGIC consists of the virtual combination of GRACE-C (NASA and DLR) and NGGM (ESA), with staggered deployment of the two complimentary satellite pairs, and will be fully operational in 2032 after the launch of NGGM. MAGIC will be capable of delivering novel products of higher temporal (sub-weekly) and spatial (170km) resolution, with shorter latency and higher accuracy, leading to new science, applications, and operational services. In preparation for MAGIC, ESA and NASA held a user workshop in November 2023 to discuss joint science and applications. The workshop included over 120 participants from 15 different countries and resulted in a final report that highlighted key topics related to joint science and applications supported by MAGIC. ESA and NASA established a MAGIC Working Group to collaborate on the joint science and applications plan on MAGIC, consisting of 8 European and 8 US experts. The two agencies will hold a joint session on MAGIC at ESA's Living Planet Symposium 2025 in Vienna in June 2025.

Gravitational Reference Advanced Technology Test in Space (GRATTIS)

he GRATTIS mission was selected for funding in May 2024, under NASA's In-Space Validation of Earth Science Technologies (InVEST) Program. GRATTIS will demonstrate two separate technologies for measuring non-gravitational accelerations with high precision in a space environment, and it is planned to launch in 2027. Two technology demonstrations will fly on the same spacecraft bus, which is a commercial ESPA-class microsatellite, and will launch on a SpaceX Transporter mission. These technologies are relevant for future gravity field missions.

The first technology demonstration, led by the University of Florida, will be for the Simplified Gravitational Reference Sensor (S-GRS), which is estimated to be an order of magnitude more sensitive than the accelerometers flown on GRACE-FO. The S-GRS concept is a simplified version of the flight-proven LISA Pathfinder GRS. GRATTIS will fly two identical S-GRS sensors mounted around the center of mass of the satellite, and will measure linear and angular accelerations in three dimensions.

The second technology demonstration, led by the University of Arizona, is for the Optomechanical-Distributed instrument for Inertial sensing and Navigation (ODIN) payload. This is a low-cost, size, weight, and power instrument capable of measuring linear and angular accelerations at the $10^{-9}\mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}$ and 50 microrad/$\sqrt{\mathrm{Hz}}$ level, respectively. ODIN consists of an array of optomechanical inertial sensors to measure non-gravitational accelerations in 3-dimensions.

Quantum Gravity Gradiometer Pathfinder (QGG-Pf)

In 2024, NASA initiated a focused effort to develop a QGG-Pf instrument to be delivered for on-orbit testing no earlier than 2030. QGG-Pf is a technology demonstration project that will enable and validate key future remote sensing quantum capabilities, inform decisions, and reduce risk in developing a future science-grade instrument. The mission concept will demonstrate relevant Earth gravity gradient measurements in an end-to-end LEO mission with targeted sensitivity of at least 100 mE/$\sqrt{\mathrm{Hz}}$. The end-to-end concept includes the physics protocol for thermal cloud generation and subsequent cooling, optical transport, atom interferometry, and detection.

Cold Atom Rubidium Interferometer in Orbit for Quantum Accelerometry (CARIOQA)

The Cold Atom Rubidium Interferometer in Orbit for Quantum Accelerometry (CARIOQA) project has progressed significantly from its start in December 2022. It aims to develop quantum gravimeters/accelerometers in space within the next decade through a Quantum Space Gravimetry Pathfinder Mission. The long-term vision is that this technology will be used to measure temporal variations in the Earth's gravity field to monitor climate change and support the development of mitigation and adaptation measures. Over the last 2 years, two separate, but related efforts have progressed in the form of a Pathfinder Mission Preparation (CARIOQA-PMP), which aims to develop the engineering model of the quantum sensor, and subsequently a Phase A development (CARIOQA-PHA) that began in January 2024 for a 1-year duration. The CARIOQA-PHA was focused on the formalization of technical demonstration needs, the study of system operations concepts, and finally, the confirmation of mission feasibility of the Quantum Space Gravimetry Pathfinder Mission within the decade. CARIOQA is funded under the EU Horizon Europe program and consists of 17 European consortium partners.

JWG 2.3.1 Spatial Leakage Mitigation in Satellite Gravimetry

Chair: Eva Boergens (Germany)
Vice-Chair: Bramha Dutt Vishwakarma (India)

Activities during the period of 2023-2025

The Joint Working Group "Spatial Leakage Mitigation in Satellite Gravimetry" held its kick-off meeting alongside EGU 2024 in Vienna. During the reporting period, the work of the JWG focused on fundamental discussions regarding the definition of leakage. The JWG agreed that leakage originates from two sources: the damping of the gravity field due to satellite altitude (upward continuation) and the filtering of noisy solutions. Leakage encompasses both effects and represents the inability to accurately locate mass changes spatially. It should also be noted that the term "leakage out" should be avoided, as from a mathematical perspective, such a concept does not exist.

The JWG decided to further investigate the limits of gravimetric resolution. This resolution refers to the minimum mass change that can be detected by GRACE(-FO) at satellite altitude. The investigation is ongoing and based on realistic simulations.

Work on a review paper of leakage mitigation methods is currently underway, led by Bramha Dutt Vishwakarma and other members of the JWG.

An application for funding a PhD student to review and refine leakage mitigation methods has been submitted to the German Research Foundation and is awaiting a final decision.

6 SC2.4 Gravity and Geoid

SC 2.4a Gravity and Geoid in Europe

Chair: Joachim Schwabe (Germany)
Vice-Chair: Thomas Grombein (Germany)

Overview

For more than two decades, SC 2.4a (with its predecessor Commission Project CP 2.1 "European Gravity and Geoid Project" (EGGP)) was chaired by Heiner Denker (Institute of Geodesy (IfE), Hannover). During this period, a tremendous amount of gravity and elevation data has been collected from various sources. The data were mainly used to compute gravimetric quasigeoid models covering the entire continent known as the "European Gravimetric Geoid" (EGG, latest version EGG2015).

Dr. Denker has recently resigned from the role. Since December 2024, the subcommission is chaired by J. Schwabe (co-chair T. Grombein). The gravity database cannot be transferred since the data were provided mostly subject to confidentiality agreements. Thus, in the coming years the foremost concern will be to recollect the data and rebuild the database from scratch. While this also offers the chance for a new and clean start, it also means that a new version of the EGG is not likely to be released before 2028.

This challenging task may be facilitated by using the latest and quality-controlled datasets for the national geoid models, and by building upon exchanges with the network of experts in regional geoid modeling initiatives, such as the NKG geoid, European Alps Geoid project, the Geomed project, etc. Most of the national points of contact are already known to the EUREF Working Group. As a first step, we will therefore reach out to (re-)provide the latest and official national datasets to the IAG SC 2.4a under defined terms and conditions. Thereby, we will aim for pragmatic and sustainable solutions so that, in the future, confidential data may at least be stored and used permanently within the SC (e.g. with the acting chair).

GNSS-based height determination has gained widespread application, and its relevance is still increasing. On the European scale, this calls for a height transformation grid which is tailored to the latest realizations of ETRS89 and EVRS. The task to derive and implement such a "European Height Reference Surface" (EHRS) has been taken on within IAG SC 1.3a "Regional Reference Frames Europe" (EUREF) by a Working Group "European United Height Reference" (WG EUHR), established in 2021 and also chaired by J. Schwabe. The pan-European gravimetric quasigeoid model is a key input for the EHRS. Hence, the work within IAG SC 2.4a is closely connected with the goals and activities of the EUREF Working Group. Bundling these activities will overall benefit the different communities and perspectives (gravity field modeling vs. reference frames, science vs. mapping agencies vs. end users).

Short summary

The previous chair of SC 2.4a, Heiner Denker, has resigned from the role. The SC is now led by J. Schwabe (co-chair T. Grombein). The gravity data for the European

Gravimetric Quasigeoid (EGG) cannot be transferred to the new chairs due to confidentiality agreements. Thus, the relevant data have to be collected again from scratch. Extended collaboration with the IAG SC 1.3a (EUREF) will not only facilitate this task but also create synergies in general, between the scientific communities focusing on gravity field modeling and reference frames on the side and different user groups on the other side.

SC 2.4b Gravity and Geoid in South America

Chair: Gabriel Guimarães (Brazil)
Vice-Chair: Ayelen Pereira (Argentina)

This report intends to cover most of the activities in South America related to gravity field determination. Therefore, sub-commission 2.4b acknowledged the *Instituto Geográfico Agustín Codazzi* (IGAC) - Colombia, the *Instituto Geográfico Militar de Uruguay* (IGM-UY), and the *Centro de Estudos de Geodesia* (CENEGEO) from Brazil for their contributions.

Improvements in gravity databases

South America

A big effort was carried out by many different organizations in the last four years to improve the gravity data coverage all over South America. As a result, a total of 924,237 points of gravity data are now available for geoid determination. (Fig. 9) shows the new (red points) and old (blue points) gravity data available. The 2,160 new gravity observations have been carried out with LaCoste&Romberg and/or CG5 gravity meters. GNSS double frequency receivers have been used to derive the geodetic coordinates of the stations.

Brazil

Since July 2023, a total of 2,160 new gravity stations have been measured by the following organizations: CGED (Geodesy Coordination) of IBGE, *Universidade de São Paulo*, *Escola Politécnica*, *Departamento de Engenharia de Transportes* (EPUSP-PTR),*Universidade Federal de Uberlândia* (UFU), *Instituto Geográfico e Cartográfico de São Paulo* (IGC), *Fundação de Apoio à Pesquisa do Paraná* (FUNTEF-PR), *Universidade Tecnológica Federal do Paraná* (UTFPR), *Itaipu binacional* and *Centro de Estudos de Geodesia* (CENEGEO), see (Fig. 10). The last gravity surveys in the Minas Gerais, São Paulo, and Paraná states are shown in the zoomed-in (Fig. 10).

Colombia

From 2023 to 2024, the *Instituto Geográfico Agustín Codazzi* (IGAC) conducted an extensive densification campaign of the National Gravimetric Network. In 2023, gravimetric observations were performed at a total of 74 stations. In 2024, the campaign reached its largest scale, successfully completing measurements at 337 stations across

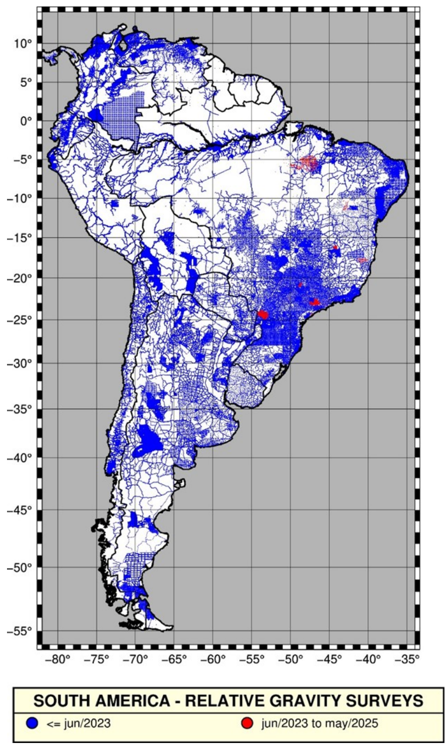


Fig. 9. South America relative gravity surveys.

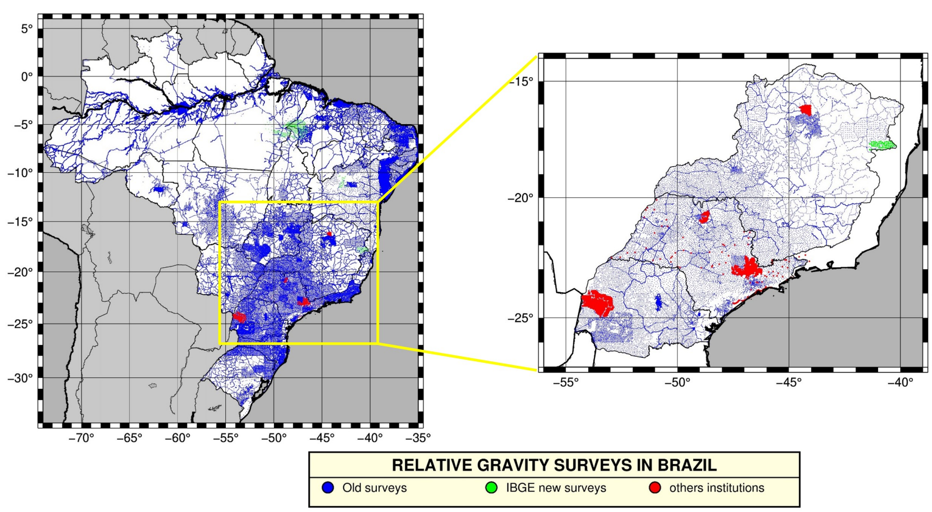


Fig. 10. Brazil new relative gravity surveys

various departments of the country. Overall, during these two years, relative gravity measurements were executed at a total of 411 stations (Fig. 11 (a)), marking a significant advancement in strengthening the national gravimetric infrastructure. During 2024, significant progress was made in collecting gravity data to establish points linked to the International Height Reference Framework (IHRF), in accordance with the guidelines of SIRGAS Working Group III. A total of 100 points were measured, achieving 94% of the annual goal of 106 points (Fig. 11 (b)). However, the remaining six points could not be addressed due to logistical challenges. These points are located in areas that are difficult to access by land, encountering issues such as inadequate road infrastructure, public order concerns, and special territorial coordination requirements.

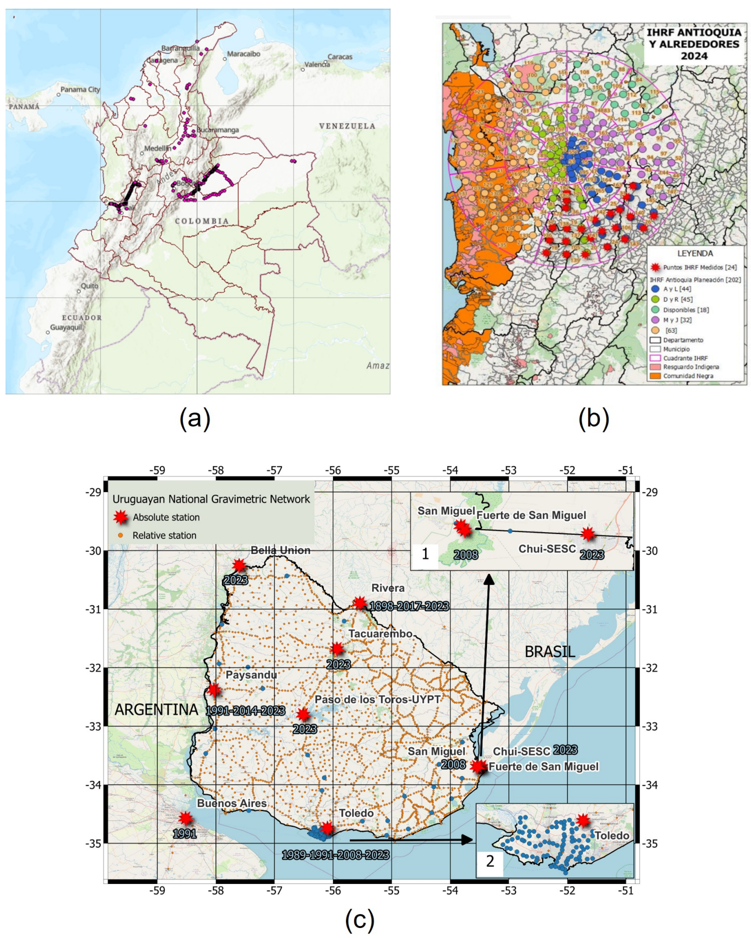


Fig. 11. Colombia and Uruguay new relative gravity surveys

Uruguay

Since 2023, 130 new relative gravity stations (Fig. 11 (c)) were measured as part of local and IHRS/F projects using one LaCoste&Romberg, and one Scintrex CG-5 gravimeter. All the stations were connected to the Uruguayan National Gravimetric Network (UNGN). The gravity network was simultaneously readjusted using the GRAVNA program (Wenzel, 1997), based on nine absolute gravity stations established between 1989 and 2023, and 2502 relative ones measured between 1966 and 2024. The mean standard deviation of a gravity station from this readjustment was 24 microgals, showing excellent agreement between the three different absolute gravity meters and among the reoccupation of some of the stations across different epoch (Subiza Piña, 2024a; Subiza Piña and Timmen, 2024; Subiza Piña, 2024). Figure below illustrates the current situation of the UNGN. The orange stations represent the previously existing relative stations, the blue ones indicate the new relative stations, and the red stars denote the absolute gravity stations, accompanied by the data from each measurement. Two enlargements on the right show (1) the boundary area with Brazil, where there are three absolute stations, and (2) a relative densification conducted in the capital city of Montevideo with more than 80 relative stations.

Absolute gravity measurements

In Brazil, the IGC owns a gravity meter A-10 under the responsibility of the University of São Paulo. Fig. 12(a) shows the establishment of absolute stations in Brazil. The most recently established stations were Chuí_SESC in Rio Grande do Sul state and Rio Brilhante in Mato Grosso do Sul state, both in 2023. Fig. 12(b) shows the establishment of 22 absolute stations in Paraguay. The stations were measured by the Universidad Nacional de Asunción (FIUNA/PY) and EPUSP-PTR supported by IGC and CENEGEO. The Ministry of Energy and Mines (MEN) with National Geological Service (SGN) at Dominican Republic, with CENEGEO – Centro de Estudos de Geodesia, Brazil, have been working in the last few years in order to establish the Local Reference Gravity (LRG) in the country as well as to improve the gravity coverage. A total of 12 absolute measurements have been accomplished (Fig. 12(c)) and 655 densification points observed along the main roads in the country. In the meantime, MEN had the cooperation of the Colombian *Instituto Geografico Agustin Codazzi* in order to undertake 10 gravity reference points based on the LRG, thus developing a first order gravimety reference.

Geoid Models

SAM_ GEOID2023 and SAM_ QGEOID2023 models in South America

The South America gravimetric geoid and quasi-geoid models, SAM_GEOID2023 (Fig. 13) and SAM_QGEOID2023 respectively, encompass a latitude range from 15ºN to 58ºS and a longitude range from 99ºW to 32ºW, with a resolution of 5 arc minutes (Guimarães et al., 2024) (Figure 4). A total of 959,930 terrestrial gravity values were utilized. The model was computed using the Meissl-modified Stokes kernel by Vaníček and Kleusberg (1987), with the SHGeo software package developed by the University

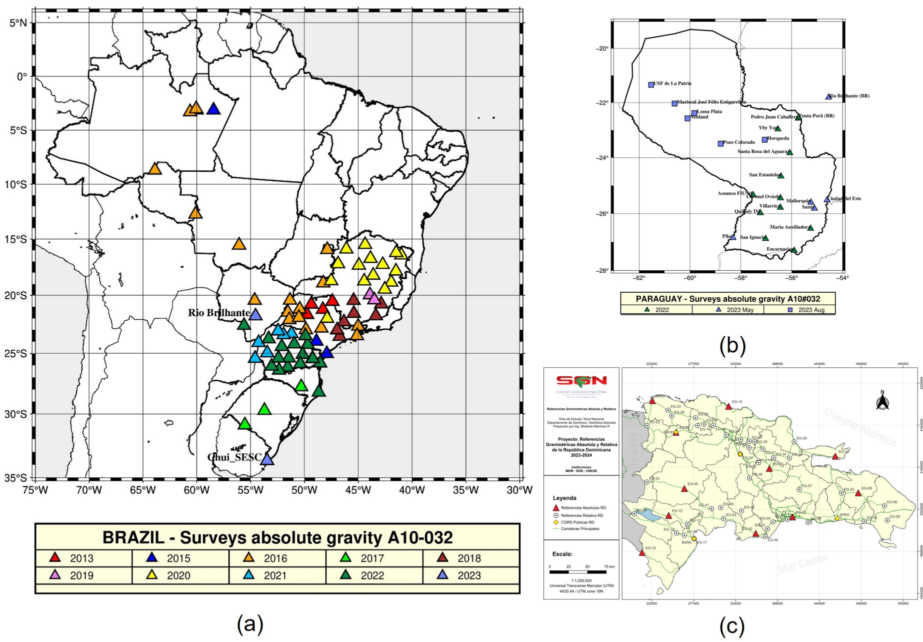


Fig. 12. Absolute gravity stations in Latin America

of New Brunswick, Canada. The downward continuation process was applied. The global geopotential model XGM2019 up to degree and order 300 was employed to represent the reference gravity field long wavelength components. The digital terrain model SRTMv3 was selected for the computation of topographical and atmospheric effects (referenced to the Earth and geoid surfaces), while the Grav_32.1 gravity field model was employed in oceanic regions. Because some countries in South America are based on normal height systems, the geoid model was converted to a quasi-geoid model using the classical geoid/quasi-geoid separation term by Heiskanen and Moritz (1967). The models were inferred by GNSS/levelling stations distributed in seven countries, with the difference standard deviation varying from 0.36 m in Ecuador to 0.07 m in Uruguay. Grids of the models are available in: https://www.isgeoid.polimi.it/Geoid/America/Southamerica/southamerica2023_g.htm.

Brazil - GEOID-SP-2024 models in São Paulo state

The last years, the Laboratório de Topografia e Geodesia, Escola Politécnica da Universidade de São Paulo (LTG/EPUSP), recently associated with Centro de Estudos de Geodesia (CENEGEO), have been working in partnership with Instituto Geográfico e Cartográfico de São Paulo (IGC) to fill in the various gravimetric gaps in São Paulo state, establishing 1,326 new gravimetric points. Two new geoid models called GEOID-SP-2024-GGM100 (Fig. 14) and GEOID-SP-2024-GGM360 and two quasi-geoid models called QGEOIDSP2024GGM100, QGEOIDSP2024z-GGM360 were com-

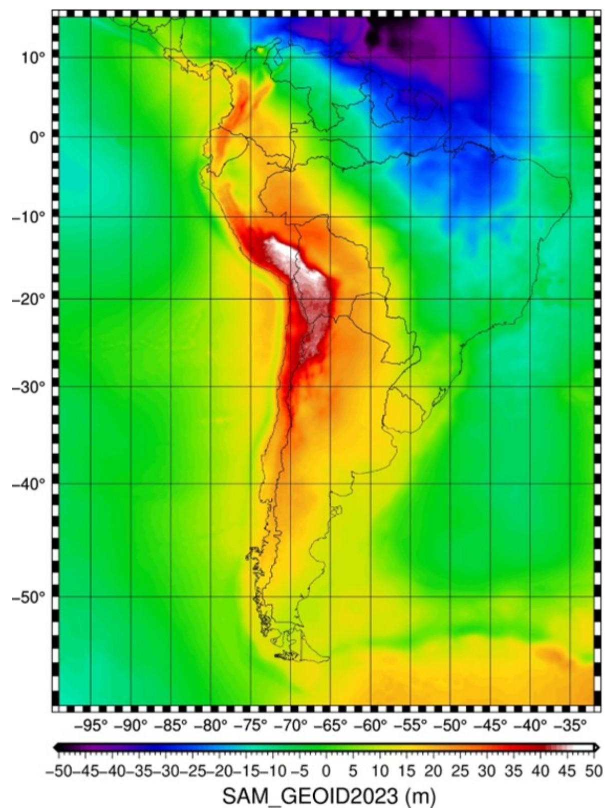


Fig. 13. SAM_GEOID2023 geoid model

puted (Matos et al., 2024). These models are limited by 27ºS and 18ºS in latitude and 56ºW and 43ºW in longitude. A total of 65,910 terrestrial gravity values were utilized. The Stokes-Helmert geoid software (SHGEO) from the University of New Brunswick (UNB), Canada, which is an accurate scientific package for gravimetric geoid determination based on the Stokes-Helmert approach, was used. The following datasets were used for the gravimetric geoid calculation and validation in the area: gravimetric ground data; XGM2019e geopotential model (degrees 100 and 360) to calculate the long and medium wavelength components of the gravity anomaly; the UNB developed UNB_TopoDensT_2v02 global laterally varying topographic density model (Sheng et al., 2019); and SRTMv3 DEM data. The latter was used for the calculation of topographic effects and downward continuation. The short wavelength component was estimated by the Fast Fourier Transform (FFT) method, with the kernel modification proposed by Vaníček and Kleusberg (1987). The quasigeoid models were also calculated using the relationship between geoidal height and height anomaly given by Heiskanen and Moritz (1967). GNSS/levelling points (IBGE and IGC) were used for model validation and standard deviations of 13 cm (degree 100) and 8 cm (degree 360) in this analysis were obtained.

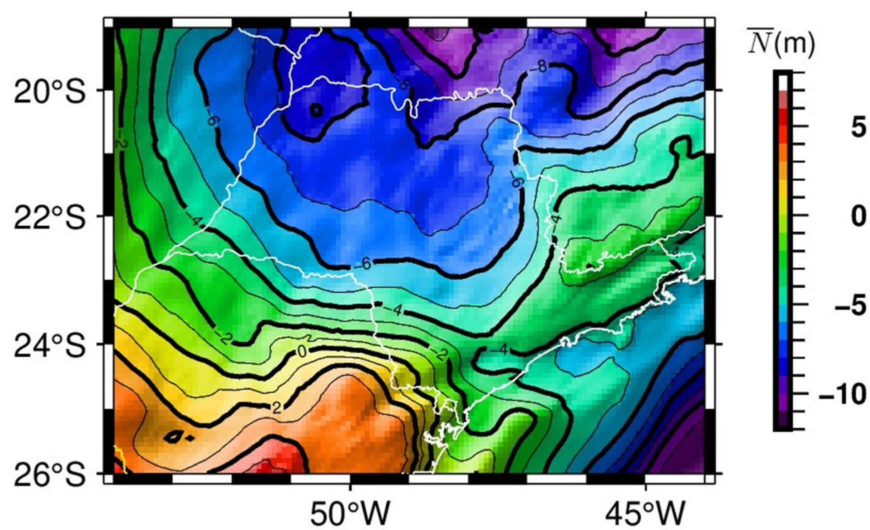
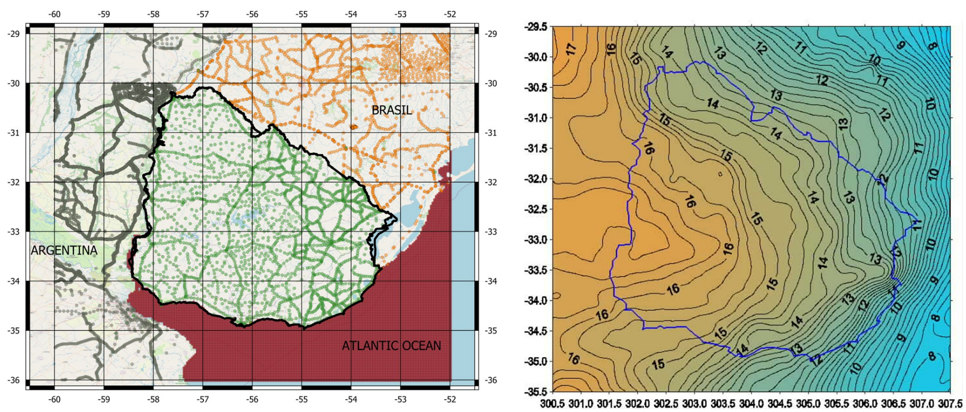


Fig. 14. GEOID-SP-2024-GGM100 geoid model.

Uruguay

A new quasi-geoidal, geoidal, and hybrid model was calculated in 2023, named UrugQ-Geoide110, UrugGeoide110, and IGM110, respectively. They ranged from -60 to -52 degrees of longitude and -29 to -35 degrees of latitude (Subiza Piña, 2024a; Subiza Piña, 2024). These models replaced the previous 2007 versions of the similar ones. The new models are available at the IGM as well as the International Service for the Geoid site. A new strategy for taking account of the terrain and gravity data allows for a resolution of 30” for terrain and 1´ for gravity data. The GRAVSOFT geophysical package (Forsberg and Tscherning, 2015) and the remove-calculate-restore technique were used. A comparison of altitudes using the geoid model and 45 control stations gave a mean of 0.01 m of difference and a standard deviation of 0.07 m. The separation between the quasi-geoid and geoid surfaces in Uruguay is less than 2 cm. Fig. 15(a) shows more than 20,000 station gravity data used at continental and marine areas (colors: brown for Argentina, orange for Brazil, green for Uruguay, and red for marine data). Fig. 15(b) shows the final UruGeoid100 (2023) with 0.25 m interval isolines. It is expected to update the geoidal models in the medium term, as soon as new geopotential models or new gravity data are available.



(a) (b)

Fig. 15. Gravity data and UruGeoid100 model

Gravity and Geoid Webinar and Events

The 14th International School on "The Determination and Use of the Geoid" took place in Buenos Aires, Argentina, in 2023. This event offered essential training on geoid determination and its practical applications. The school was organized in collaboration with the International Service for the Geoid, part of the International Association of Geodesy, and the Pan American Institute of Geography and History. A total of 40 participants (Fig. 16) from 14 different countries attended the school.

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Fig. 16. Geoid school attendees

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SC 2.4c Gravity and Geoid in North and Central America

Chair: Jianliang Huang (Canada)
Vice-Chair: David Avalos (Mexico)

Overview

Activities in North and Central America are currently driven by the three national geodetic agencies in Canada, USA and Mexico, with relevant contributions from the academia. Advancements have been made in the gravity field and geoid modeling at national and regional scale with promising results. Remarkably, the collaboration among the three agencies has been constructing a regional geoid model with an extended coverage to include Greenland, Iceland, Central America, the Caribbean Sea and the northern parts of South America.

The sections below highlight major activities of the sub-commission from 2023 to 2025. The list is not necessarily exhaustive.

International collaboration

The geodetic agencies from Canada, USA and Mexico maintain close communication through meetings on a regular basis, where geoid specialists share and discuss geoid modeling methods, software, data and results. By the middle of 2025, this collaboration yields common terrestrial and marine gravity datasets, global and North American digital elevation models, the Earth's gravitational model and an airborne gravity dataset covering USA and its territories with extensions into Canada and USA from borders.

Particularly the geoid teams in the three agencies have integrated three geoid models into a common static geoid model (GEOID2022) over North America by the middle of 2025. Other products include a dynamic geoid model, deflection of the vertical, the refined Bouguer gravity grid, and the geoid-to-quasigeoid separation term.

Another collaborative effort is carried out among the geodetic agencies of Mexico, Guatemala, El Salvador and Costa Rica, maintaining an open communication by annual meetings on which the most recent information is shared and particular interests are discussed.

Development of the North American-Pacific Geopotential Datum of 2022 (NAPGD2022)

NAPGD2022 is defined by parameters in Table 1. It will modernize the vertical datum of the US National Spatial Reference System (NSRS) under the leadership of NGS and update the NAVD 88 height reference system to a geoid-based dynamic (or time-varying) height reference system. This new datum spans about one-quarter of the Earth surface covering one whole continent, Greenland, north-west Atlantic and north-east Pacific, central Americas, parts of South Americas, Europe and Africa (see Figure 17). It also contains two separate datums for two Pacific regions covering Guam and Commonwealth of Northern Mariana Islands and American Samoa. The geopotential parameters such as geoid height and deflections of the vertical are determined at the geographic spacing of one arcminute and their true geographic resolution varies from place to place and is dependent on the sampling density and quality of surface gravity data, and the resolution of digital elevation model (DEM).

Table 1. Defining parameters of NAPGD2022

Definition and Parameters	**Value and realization**
W_0	62,636,856 m^2/s^2
GM	$3.986004415 \times 10^{14}$ m^3/s^2
Realization	GEOID2022
Geometric RF	NATRF2022
Height (type)	Orthometric $H^o(\varphi, \lambda) = h(\varphi, \lambda) - N(\varphi, \lambda)$
Tide system	Tide Free
Velocity of height	Time dependent $\dot{H}^o(\varphi, \lambda) = \dot{h}(\varphi, \lambda) - \dot{N}(\varphi, \lambda)$
Velocity of geoid height	Time dependent $\dot{N}(\varphi, \lambda)$
Reference epoch	2020.0

The static geoid model (GEOID2022) has been agreed upon with the geoid teams and is shown in Figure 17. This combined model is a simple average of 1 CGS model, 1 NGS model, and 1 INEGI model. Since INEGI computes their model over a more limited area (see Figure 19), the INEGI contribution is limited to the Mexico land mass. So, outside of Mexico, the model is a 50/50 split of CGS and NGS models, while inside of Mexico, it is the INEGI model.

A preliminary standard deviation model for GEOID2022 has been also developed by NGS (see Figure 18). It was estimated as a quadrature sum of tapered formal errors from GOCO06s and propagated uncertainties of surface gravity contributions from terrestrial point data and satellite altimetry. The surface gravity component of the geoid error grid was generated from linear propagation of the formal uncertainties of gridded gravity data output by least-squares collocation. Because both grids altimetry and terrestrial gravity contributions to GEOID2022 were created using some form of interpolation, the grid cells are necessarily correlated with a typical half-wavelength scale on the order of tens of kilometers. Sparse gravity data are expected to be more correlated across distances, while dense data should be more spatially independent. While these scales are comparable to the grid resolution for 5 arcminute geoid grids, permitting correlations to be ignored, propagation of correlated gravity errors at a 1 arcminute grid resolution without accounting for correlation leads to underestimation of geoid uncertainties by an order of magnitude. We therefore endeavored to account for these uncertainties.

As a simplifying assumption, we used the a priori correlation functions in the error propagation. Over land and coastal margins, we used the default GRAVSOFT-/GEOGRID correlation function with a scale parameter of 25 km, corresponding to a

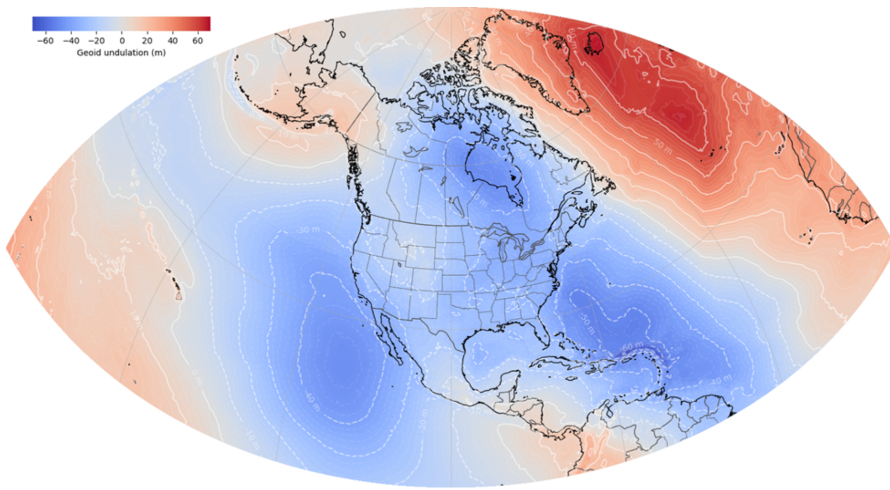

Fig. 17. Static geoid model GEOID2022 Beta version over North America

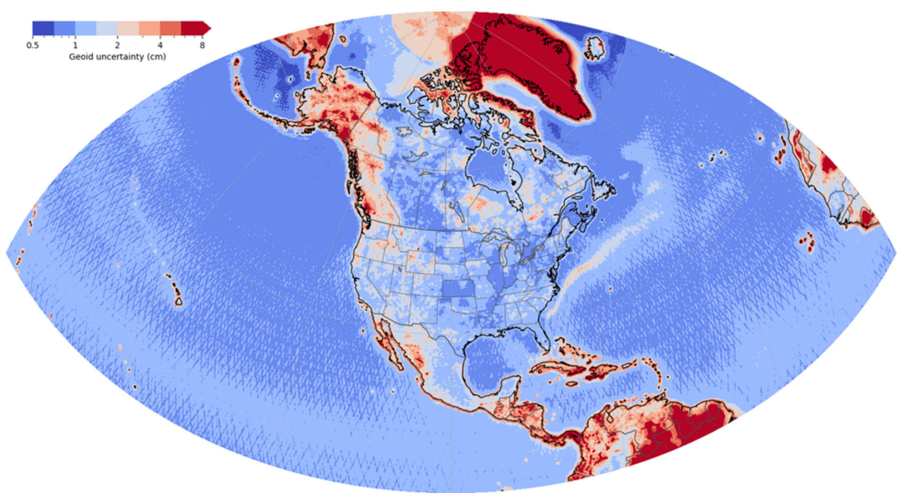

Fig. 18. Preliminary standard deviation model of static GEOID2022 beta.

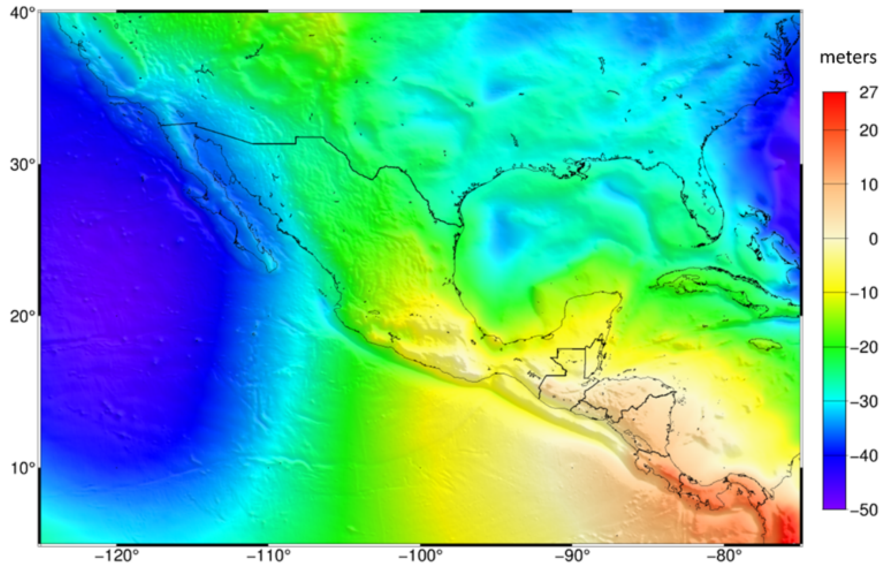

Fig. 19. The INEGI geoid model for Mexico.

correlation half-width of about 42 km. Over open ocean, we used a 15 km half-width Gaussian function. This uniform assumption for the correlation function generally leads to a pessimistic error estimate where gravity data is abundant, while the error estimate is more accurate where gravity is sparse. This pessimistic bias was addressed by linear scaling of these grids to approximately match Geoid Slope Validation Survey residuals. The actual computation was performed using 2D FFTs in a 6x6 arc-degree window to bypass redundant calculations and onerous memory requirements for storing and manipulating a massive covariance matrix. Instead, the correlation function and Stokes kernel were precomputed at the equator and the gravity uncertainty grid was rotated down to the equator for power spectral density estimation and convolution. This approach was found not to be viable north of 87° N, so a local linear approximation based on spectral-domain relationships between geoid uncertainty and homoscedastic uniform correlated gravity uncertainty was used instead.

Future work may consider stochastic methods of estimating the geoid uncertainty and accounting for spatial variability in the correlation scales.

As the dynamic component of GEOID2022, a preliminary dynamic geoid model (or geoid velocity model) over North America was derived from GRACE's satellite gravimetry data and glacial models over Greenland and Alaska by NGS (see Figure 20). Other products can be found and downloaded at NGS's ALPHA website (https://alpha.ngs.noaa.gov/NAPGD2022/).

Canada adopted a geoid-based vertical datum – the Canadian Geodetic Vertical Datum of 2013 in 2016, which was realized by the Canadian Gravimetric Geoid Model of 2013a (CGG2013a). Figure 21 shows a full range of the differences between static GEOID2022 beta and CGG2013a over the land part of Canada (left panel), and a bar

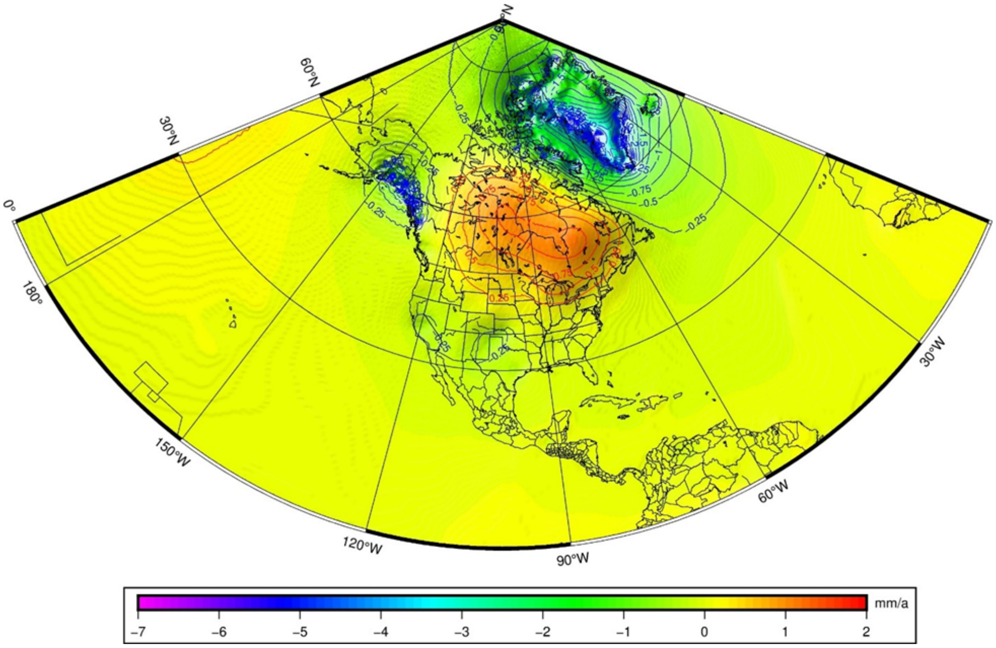

Fig. 20. A preliminary dynamic geoid model over North America.

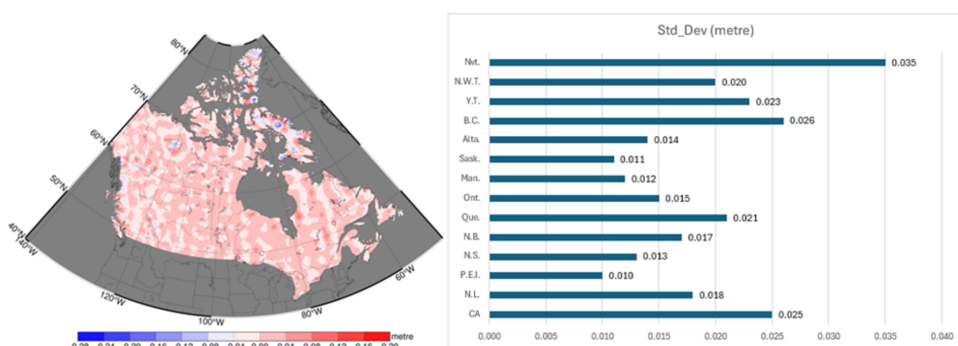

Fig. 21. The difference between CGG2013a and static GEOID2022 (left), statistics of differences over Canadian provinces (right).

graph showing standard deviations of the differences with each province and territory (right panel). The differences are caused by the update of DEMs, new satellite gravity model, the use of NGS's airborne GRAV-D data along the borders, marine gravity data along the coast, to a less extent by land gravity data and the method difference between CGS and NGS.

This Sub-Commission has presented the development of NAPGD2022 at annual AGU's and CGU's conferences, GGHS2024 and was invited to give a talk in a geoid workshop (see References).

International Great Lakes Datum

The Hydraulic Corrector Working Group has made substantial progress toward validating the geoid model GEOID2022 as part of its effort to modernize dynamic water level determination across the Great Lakes. The group computed dynamic water levels by integrating water level observations, GNSS ellipsoidal heights, levelling data, and the GEOID2022 model across 97 water gauges (54 permanent and 43 seasonal or temporary) distributed over Lakes Superior, Michigan, Huron, Erie, and Ontario. The resulting dynamic heights display a high level of internal consistency, with standard deviations between gauges on each lake ranging from just 1 to 1.5 cm. This level of agreement—an order of magnitude better than IGLD85—strongly indicates that the GEOID2022 model is accurate to at least that level of precision over the region.

Geoid Uncertainty

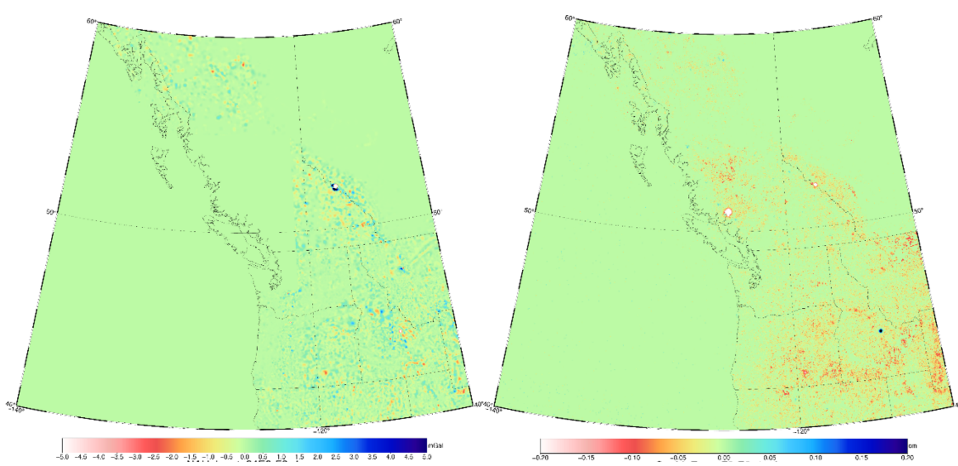

Fig. 22. Difference between Helmert gravity grid (left), geoid uncertainty estimates (right) as a result of considering DEM error on terrain corrections

A formal error propagation through the geoid determination steps of the Stokes-Helmert method was carried out by CGS, resulting in an absolute uncertainty estimate for GEOID2022—commonly referred to as the internal geoid error. The error sources considered in the CGS model include terrain roughness, terrestrial gravity observations, shipborne and satellite-altimetry-derived gravity data offshore, interpolation errors from least-squares collocation, and inaccuracies in the Earth's gravitational model.

An additional experiment was conducted to assess the impact of digital elevation model (DEM) errors on terrain corrections applied during geoid determination. The nominal DEM error estimates were treated as variances at the DEM points, and spatial covariances were modeled using an estimated correlation length. Results indicate that incorporating DEM error into terrain correction alters the Helmert gravity grid by several tens of mGals and affects the geoid height uncertainty with a few centimetres (see Figure 22).

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SC 2.4d Gravity and Geoid in Africa

Chair: Hussein Abd-Elmotaal (Egypt)
Vice-Chair: S.A. Benahmed Daho (Algeria)

Main activities (2023–2025)

Abd-Elmotaal et al. (2023a) evaluated the recent African gravity databases V2.x using a new set of gravity data along Egypt and the Mediterranean Sea. Seitz et al. (2023) elaborated a very interesting study to deduce exact expressions for the external gravitational field of a homogeneous ellipsoidal shell to be used as a reference for testing gravity modelling software. Abd-Elmotaal at al. (2023b) studied the effect of the crustal density on the gravity interpolation at the large data gaps of Africa. Makhloof et al. (2023) have computed a gravimetric geoid for Egypt based on properly application of Helmet's method of condensations within the window remove-restore technique. Abd-Elmotaal and Makhloof (2023) have integrated the available altimetry-derived gravity anomalies with the Ship-borne gravity data for Africa producing a common gravity data set for the ocean area around Africa.

Ashry et al. (2023a) studied the impact of the digital height models resolution on the gravity anomalies and the geoid undulations in Egypt. Ashry et al. (2023b, 2024) elaborated studies towards the realization of the African and the International Height Systems using relativistic geodetic approaches. Abd-Elmotaal (2023) studied the effect of gravity data coverage on the gravimetric geoid determination in Africa.

Abd-Elmotaal and Makhloof (2023) suggested two powerful alternative techniques for fitting the gravimetric geoid for Egypt. Abd-Elmotaal et al. (2024a) carried out a comparison study of the different approaches for combining the gravity field wavelengths for Egypt.

Abd-Elmotaal et al. (2024b) studied the effect of implementing the Moho depths on the gravity interpolation at large data gaps in Africa. Abd-Elmotaal et al. (2024c) generated the updated gravity database for Africa, AFRGDB V2.3, using RTM Technique. Abd Elmotaal et al. (2024d, 2025a) generated a Moho model for Africa. This Moho model has been used to generate a new gravity database for Africa (Abd-Elmotaal et al., 2025b). Abd-Elmotaal and Kühtreiber (2025) proposed three techniques for gross errors detection for the African gravity database, including smart and artificial intelligence techniques.

Odera et al. (2024) demonstrated effective application of tailored gravity-field model (developed by combining global gravity models, topographic residual gravity, and terrestrial gravity observations) in reproducing local gravity field, hence accurate quasigeoid modelling in data-sparse regions (a case study in Cameroon and South Africa). Their findings underscore the potential of tailored gravity-field models in developing accurate quasigeoid models, particularly in regions with limited gravity data coverage such as Africa.

Mphuthi and Odera (2025) carried out empirical investigations towards establishing a geoid-based vertical datum, consistent with the International Height Reference System (IHRS) over South Africa. They found that the local land levelling datum over South Africa should be modernised by adopting either normal or orthometric height systems. Further, the tide gauge benchmark (TGBM) at Cape Town (CPT) should be adopted (out of the four TGBMs over South Africa) when transforming a selected height system onto the IHRS.

Future Activities

A new geoid model for Africa implementing Moho information is undertaken meanwhile and is going to be presented in the IAG Scientific Assembly, Rimini, Italy, September 1– 5, 2025, by Abd-Elmotaal et al. At the same IAG meeting, an Afro-Euro Unified Height System, a pioneering framework that integrates relativistic geodesy, global geopotential models, and terrestrial gravity data to bridge the vertical height systems of Africa and Europe, is going to be presented by Ashry et al.

Problems and Request

The IAG sub-commission on the gravity and geoid in Africa suffers from the lack of data (gravity, GNSS/levelling . . .). The great support of IAG is needed in collecting the required data sets. It can hardly be all done on a private basis. Physical meetings of the members of the sub-commission would help in solving the problems and would definitely contribute to the quality of its outputs. IAG is thus kindly invited to support that action.

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SC 2.4e Gravity and Geoid in the Asia-Pacific

Chair: Cheinway Hwang (China-Taipei)
Vice-Chair: Wenbin Shen (China)

Contributions

IAG Workshop on Satellite Geodesy, Gravimetry, and Geoid in the Philippines (2024)
https://iagworkshop2024.dge.upd.edu.ph/

The IAG Sub-Commission 2.4e (Geoid – Asia/Pacific) actively contributed to the **2024 IAG Workshop on Satellite Geodesy, Gravimetry, and Geoid** held in Quezon City, Philippines, from **June 4 to 6, 2024**, hosted by the University of the Philippines Diliman. The event was co-sponsored by IAG and the Philippine Space Agency, and served as a regional platform for advancing geoid modeling and gravity-related geodetic studies across the Asia-Pacific.

On behalf of SG 2.4e, **Prof. Cheinway Hwang (Taiwan)** and **Prof. Wenbin Shen (mainland China)** gave invited talks and participated in collaborative discussions:

- **Prof. Cheinway Hwang** delivered a keynote lecture titled *"SWOT-derived marine gravity anomalies: potential and challenges for coastal geoid modeling in the Asia-Pacific"*. This talk highlighted the value of SWOT satellite altimetry in improving marine gravity fields and geoid models in coastal and island-rich regions like Southeast Asia and Oceania, emphasizing comparisons with airborne and shipborne gravity data near Taiwan and the Philippines.
- **Prof. Wenbin Shen** presented recent progress in the precise geoid determination over China and Central Asia, showing advanced gravity data integration techniques and their applications in unifying vertical datums across borders.

The workshop also included technical discussions on future regional collaboration, particularly regarding cross-border geoid unification, validation of new altimetry-derived gravity fields, and joint projects involving the Philippines, Indonesia, mainland China, and Taiwan.

These activities demonstrate SG 2.4e's continued commitment to strengthening geoid modeling capabilities and regional cooperation in the Asia-Pacific region. Follow-up coordination is underway to initiate data-sharing and joint modeling efforts under SG 2.4e leadership.

7 SC 2.5 Satellite Altimetry

Chair: Xiaoli Deng (Australia)
Vice-Chair: C K Shum (United States)

Summary

This report presents major activities that have marked the IAG sub-commission 2.5 (SC2.5) over the period of 2023-2025. Sections presented in this report provide specific details regarding the activities of working groups, IAS Pilot Service and individuals within the SC2.5, which focus on integrated use of altimetry and space geodetic techniques and their applications in Earth sciences and clime change analysis. It is noted that intensive research into marine gravity field and bathymetry prediction has been conducted since 2023 due to the availability of SWOT data.

The contributions below represent the group work led by following steering members:

Prof Ole Andersen (DTU, Denmark)
A/Prof Xiaoli Deng (The University of Newcastle, Australia)
Dr Luciana Fenoglio-Marc (University of Bonn, Germany)
Prof Cheinway Hwang (National Yang Ming Chiao Tung University, China Taibei)
Prof Tao-Yong Jin (Wuhan University, China)
Prof Chung-Yen Kuo (National Cheng Kung University, China Taibei)
Prof Jürgen Kusche (University of Bonn, Germany)
A/Prof Hyongki Lee (University of Houston, United States)
Dr Hossein Nahavandchi (Norwegian University of Science and Technology, Norway)
A/Prof Fukai Peng (Sun Yat-Sen University, China)
Prof David Sandwell (Scripps Institution of Oceanography, United States)
Prof C. K. Shum (Ohio State University, United States)
Prof Xiaochun Wan (China)
Prof Sheng-Jun Zhang (China)

Workshops

International workshop on global bathymetry prediction

An international workshop on "Bathymetry Prediction with SWOT Gravity Anomaly using Machine Learning Methods", led by Profs David Sandwell and Ole Andersen, was held at the Technical University of Denmark (DTU) in November 2024. The initiative brought together geophysicists, oceanographers, and machine learning researchers to develop global bathymetry models using SWOT gravity and neural network models. Five independent groups from Scripps Institution of Oceanography (USA), DTU, The University of Newcastle (UON, Australia), each developed a bathymetry model, all demonstrating significant improvements in depth accuracy, particularly over shallow seamounts and deep ocean trenches. This effort will lead to two forthcoming publications: one focusing on algorithm development and the other on model intercomparison. The workshop is still ongoing biweekly meetings at the time writing this report.

The introduction of high-resolution sea surface observations provided from the SWOT satellite has enabled the generation of marine gravity fields at 8-km resolution with 1-2 mGal accuracy using just one year of data, representing a major improvement over 30 years of conventional nadir altimetry. The low noise in the short-wavelength observations from SWOT is critical for bathymetric inversion, where gravity precision strongly impacts seafloor predictions. The workshop was to take full advantage of the possibilities provided with the new data from SWOT. It had the goal of utilizing the high-resolution gravity field from SWOT, together with Machine Learning (ML) models, to provide the best possible bathymetric maps from marine gravity field.

The key results from this workshop include:

1. **Bathymetry predictions** have been produced by five research groups using different ML architectures. All models demonstrate significant global improvements in accuracy (20–30%) compared to the previous bathymetry release, with the largest enhancements over continental shelves and deep ocean trenches.
2. **Cross-model comparisons** revealed how different ML design choices affect predictive performance and identified persistent challenges posed by the sparse distribution of ship-based depth soundings, which serve as training labels.
3. **Comparison with conventional physics-based inversions** showed that ML methods resolve nonlinear components in the gravity-topography transfer function, which improve prediction over seamount summits.
4. **Workshop deliverables.** Workshop agenda, participant list, and presentation materials are available at: https://drive.google.com/drive/folders/1YHf8wF0o_j3c6g0bFPKWkNbCcY5kMYJo?usp=drive_link

PRETTY workshop series - GNSS reflectometry for altimetry applications

During the period 2023–2025, activities of the group at Norwegian University of Science and Technology (NTNU) have focused on GNSS reflectometry for altimetric applications. In collaboration with an international consortium, the group designed, developed, and launched a dedicated spaceborne GNSS-R sensor aboard a 3U CubeSat measuring 10×10×30 cm, with a mass of 4.64 kg. The primary objective is to achieve precise altimetric determination of water and ice surfaces at grazing incidence angles. This miniature satellite PRETTY (Passive Reflect and dosiomeTrY), supported by the European Space Agency (ESA), was successfully launched in October 2023 and is the first CubeSat to utilize GNSS-R grazing-angle altimetry at the L5 frequency.

PRETTY has already successfully generated Delay Doppler Maps and complex waveforms, demonstrating coherent reflections along several observational track segments with strong signal returns. The group is currently celebrating PRETTY to enable high-precision altimetry results. Two peer-reviewed articles have been published (Rajabi et al., 2023; Hoseini et al.,2023).

The PRETTY mission and its early results have been presented at several international conferences including the IEEE IGARSS 2023 (Semmling et al., 2023) and 2024 (Cardellach et al., 2024), IEEE GNSS+R 2023 (Nahavandchi et al., 2023) and EGU General Assembly 2024 (Dielacher et al., 2024).

The PRETTY consortium held two post-flight workshops in collaboration with ESA officials:

- In-Orbit Commissioning Review (IOCR): 5 April 2024
- In-Orbit Demonstration (IOD): 21 November 2024

Marine gravity field and bathymetry

Since 2023, our members from different research teams (e.g., Scripps Institution of Oceanography (USA), The University of Newcastle (Australia), DTU Space (Denmark), National Yang Ming Chiao Tung University (Taiwan), Wuhan University (China), Northeastern University (China), China University of Geosciences, etc.) have made significant contributions to advancing the marine gravity field and bathymetry using SWOT data. Key accomplishments are described in this section.

Researchers at the *Scripps Institution of Oceanography*, USA, have made significant progress toward advancing the marine gravity field and bathymetry.

1. **Global marine gravity:** A paper was published in *Science* titled "Abyssal Marine Tectonics from the SWOT Mission" (Yu et al., 2024a). This study demonstrates that just one year of data from the SWOT satellite can produce a global marine gravity map with greater detail than what was possible using 30 years of traditional radar altimetry. The vertical gravity gradient (VGG) map derived from SWOT reveals fine-scale marine tectonic features, including previously unresolved small seamounts, individual abyssal hills (Fig. 23), and continental margin structures buried beneath sediments and ice. This work received press coverage from *Science News*, NASA JPL, EOS, *Live Science*, and *Physics Today*.
2. **Ongoing research on seamount catalogue and abyssal hill characterization:** The group is using the SWOT-derived vertical gravity gradient (VGG) map to identify previously undetected small seamounts. This is expected to expand the current global seamount catalogue from approximately 43,000 to nearly 100,000, with most of the new additions being small seamounts around 1 km in height. The group is also working on characterizing global abyssal hills and presented the global abyssal hill orientation at the 2024 fall AGU meeting.
3. **Ongoing research on seafloor-ocean interaction:** Yu and Sandwell are investigating how small-scale bathymetric features, particularly abyssal hills, influence the generation of internal tides and ocean mixing (Yu et al., 2024b, submitted). Using SWOT's 1-day repeat data, they are currently analyzing how seamounts distort ocean currents, potentially forming Taylor Columns, which are coherent flow structures that can enhance marine biodiversity.
   At Wuhan University, China, researchers have developed calibration techniques addressing instrumental errors in marine gravity recovery from SWOT altimetry, enabling improved coastal bathymetric predictions and gravity anomaly mapping (Ma et al., 2023). In addition, they analyzed nonlinear impacts in altimetric gravity-derived bathymetric modelling, refining seabed depth retrieval precision. A global marine gravity field (Fig. 24) has been constructed using nearly 2 years of SWOT data, which is better than the current model from 30 years of traditional altimeters.

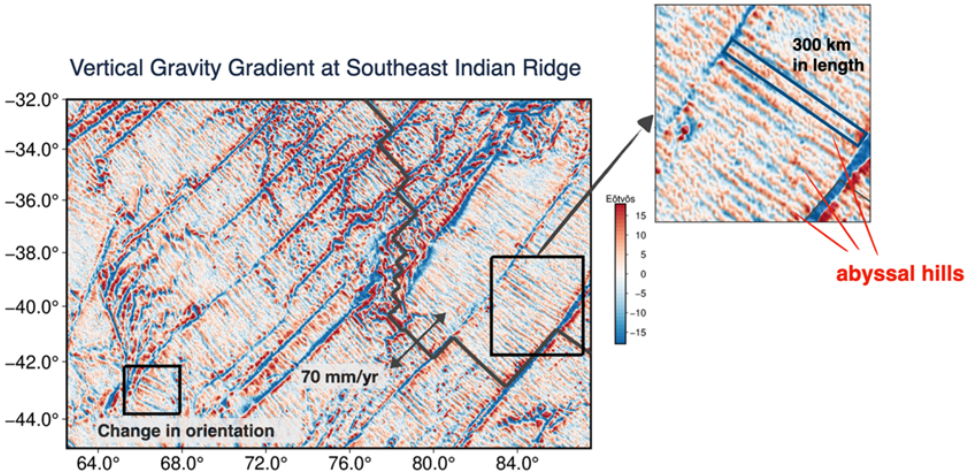

Fig. 23. Parallel abyssal hills, observed by the SWOT satellite, extend outward from a seafloor spreading center in the Indian Ocean. A change in hill orientation is highlighted within the boxed area, and individual abyssal hills are marked.

At the *Wuhan University*, China, researchers have developed calibration techniques addressing instrumental errors in marine gravity recovery from SWOT altimetry, enabling improved coastal bathymetric predictions and gravity anomaly mapping (Ma et al., 2023). In addition, they analyzed nonlinear impacts in altimetric gravity-derived bathymetric modelling, refining seabed depth retrieval precision. A global marine gravity field (Fig. 24) has been constructed using nearly 2 years of SWOT data, which is better than the current model from 30 years of traditional altimeters.

The research group at the *Northeastern University*, China, firstly developed a new global marine gravity model NSOAS24 on the basis of conventional altimetry missions (Zhang et al., 2025). Secondly, the group proposed a new method to fully utilize satellite altimetry data and ship-borne measurements in preparation of high-resolution marine gravity determination, namely the frequency-domain fusion method (Chen et al., 2024). Then, the group analyzed and proved that SWOT exhibits better marine geoid resolution capability over 2°× 2° bins worldwide between 60°N and 60°S (Chen et al., 2025; Wang et al., 2025). Last but not least, the group also focused on the submesoscale advantage for SWOT wide-swath mission and proposed an automatic eddy detection algorithm based on quadrant angle of velocity vector (Wang et al., 2024).

At the *China University of Geosciences*, researchers used satellite altimetry for marine gravity field recovery and deep-sea bathymetry inversion as follows:

1. **Marine gravity field recovery**, we proposed a spectral method of inverting full tensor of gravity gradients using altimetry-derived components of deflection of the vertical as input signals (Wang et al., 2023; Annan et al., 2024a). We named the

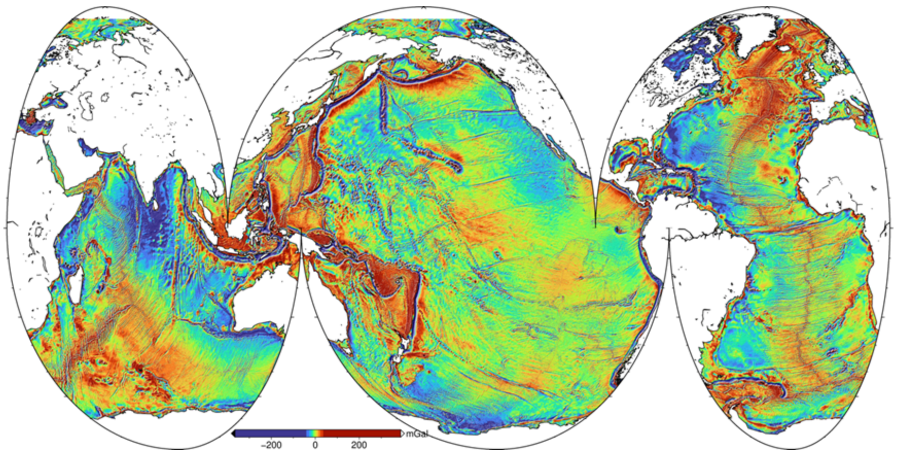

Fig. 24. Global marine gravity field from SWOT

resultant product CUGB2023GRAD, which is a model of global marine gravity gradient tensor, with a spatial resolution of 1 arcminute.

2. **Bathymetry inversion**, we proposed a deep learning-based feature extraction method of refining global seafloor prediction (Annan and Wan, 2024b). The technique initially uses convolutional neural network to learn the bathymetric features inherent in a combination of different marine gravity field signals. These learnt features are then extracted into regression trees to predict the bathymetry again, resulting in a refined global seafloor model that is more detailed than existing global seafloor models. We named the resultant model BATHY-FE (i.e., bathymetry based on feature extraction).

Research activities at the *National Yang Ming Chiao Tung University*, Taiwan, involved in marine gravity anomaly modeling, leveraging SWOT, ICESat-2, and conventional altimetry data, and refined geoid gradient extraction using regularization techniques (Yu et al., 2023; Yu et al., 2024; Li et al., 2024; Zhou et al., 2024).

At the *Liaoning Technical University*, China, researchers focused on the Tikhonov-L-curve regularization method for determining the best geoid gradients from SWOT altimetry (Yu et al., 2023) and development of an automatic identifying algorithm for seamount detection using SWOT-derived vertical gravity gradient (Yu et al., 2024).

The teams at The *Newcastle University*, Australia, and DTU have conducted research into the followings:

1. **Marine gravity field**. A new method, namely LSA3, has been developed to determine the north and east (ξ and η) components of GGs from simulated and real SWOT data in the northern South China Sea (Yu et al., 2025). The LSA3 is computationally efficient for determining the marine gravity field using SWOT data, which has improved gravity accuracy by an average of 12.0%, with a maximum improvement of 44.3%, when compared to the Sandwell V32.1 gravity field.
2. **Global and regional bathymetry prediction**. A machine learning-based global bathymetry model, referred to as BathDNN25, was developed by combining ship-

borne soundings with geophysical features derived from SWOT satellite observations. The model integrates gravity anomalies, filtered gravity, vertical gravity gradients, and slope-derived parameters to predict global seafloor topography at one-arc-minute resolution. The predicted bathymetry was validated against independent shipborne measurements (Fig. 25), demonstrating improved accuracy over conventional interpolation methods (Salajegheh et al., 2025, in review). In addition, ICESat-2 measurements have been used to study bathymetry and possible bathymetry changes from repeated tracks across Moreton Bay and Shark Bay in Australia. It is found that ICESat-2 can be used to update existing bathymetry in the coastal shallow water region (Hallstrom et al., 2024).

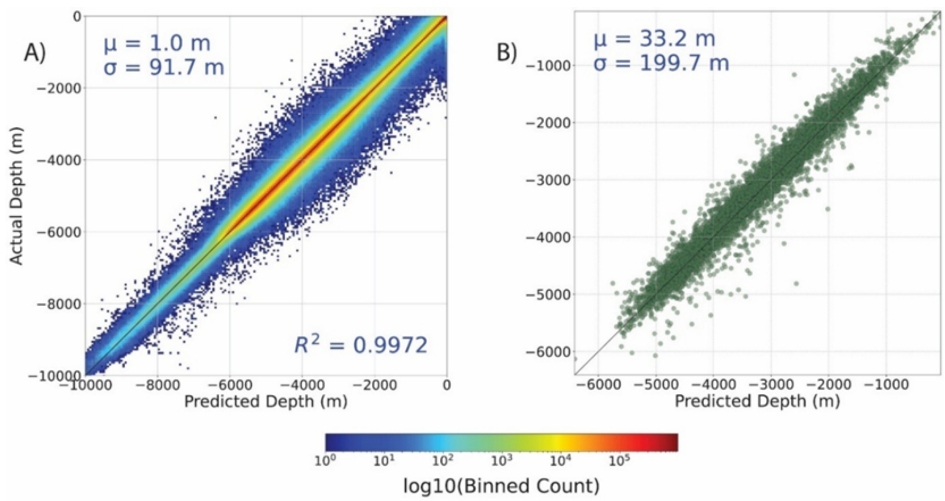

Fig. 25. Panels A and B compare BathDNN25 model-predicted depths with shipborne measurements and seamount depths, respectively. Panel A shows residuals with colour intensity representing data density, while Panel B plots predicted versus observed seamount depths with a 1:1 reference line. Mean residual (μ) and standard deviation (σ) are indicated in blue.

Satellite Altimetry Studies

SC2.5 members have worked on a wide range of satellite altimetry and its applications and studies. As examples, research activities at the DGFI-TUM (*German Geodetic Research Institute, Technical University of Munich*), involved topics in coastal and global sea levels, Arctic sea levels, ocean tides, inland water level estimation, river discharge and the exploitation of SWOT data for hydrological and ocean applications.

At the *National Yang Ming Chiao Tung University*, Taiwan, researchers have worked on satellite altimetry applications for oceanographic, hydrological, and geodetic studies. They developed automated eddy identification algorithms (Zhang et al., 2025), assessed land subsidence using Cryosat-2 altimetry and SAR imagery (Wei and

Hwang, 2025), modernized depth datums via integrated ocean tide models and precise ship positioning (Hwang et al., 2025), and advanced coastal mapping from SWOT altimetry (Hwang and Yu, 2025). They also monitored inland water storage variations in Tibet (Huang et al., 2023), and improved regional mean sea surface models and sea-level rise assessments using Jason-3 and Sentinel-3B altimetry around Taiwan (Hsiao et al., 2023).

Researchers at the *University of Bonn*, Germany, have been examining the global sea level budget from the reference altimetry missions combined with satellite gravimetry and ocean modelling. They also seek to evaluate more recent altimeters for coastal/-land applications, and have started investigating artificial intelligence methods for eddy identification.

Researchers at *Sun Yat-Sen University*, China, and The *University of Newcastle*, Australia, have published several papers on reprocessing satellite data and estimating coastal sea level rise. They are currently reprocessing ERS-2 and Envisat altimeter datasets (Peng et al., 2023, 2024a, 2024b, 2024c, 2025a, 2025b). As a result, global coastal sea level datasets based on reprocessed multi-satellite altimetry missions will cover a long period from 1996 to 2022.

The following publications represent some outcomes. A complete list of publications relative to these studies can be found in Section 6.

1. **Tides**
   - Hart-Davis et al., (2023), Altimetry-derived tide model for improved tide and water level forecasting along the European continental shelf, *Ocean Dynamics*, 10.1007/s10236-023-01560-0
   - Hart-Davis et al., (2023), Tides in complex coastal regions: early case studies from wide-swath SWOT measurements, *Geophysical Research Letters*, 51(20), e2024GL109983, https://doi.org/10.1029/2024GL109983
2. **Sea level rise**
   - Dettmering et al., (2024), The impact of different geophysical corrections on altimetry-derived sea level rise estimates - wet troposphere, *International Association of Geodesy Symposia*, 10.1007/1345_2024_262
   - Juhl et al., (2024), Evaluation of the sub-annual sea level anomalies in the continental shelf of the Southwestern Atlantic and their relation to wind variability, *Ocean Dynamics*, 10.1007/s10236-024-01621-y
   - Juhl et al., (2025), Regional daily sea level maps from Multi-mission Altimetry using Space-time Window Kriging, *Advances in Space Research*, 10.1016/j.asr.2025.04.014
   - Oelsmann et al., (2024), Coherent Modes of Global Coastal Sea Level Variability, *JGR: Oceans*, 129(12), 10.1029/2024jc021120
   - Oelsmann et al., (2024), Regional variations in relative sea-level changes influenced by nonlinear vertical land motion, *Nature Geoscience*, 137–144, 10.1038/s41561-023-01357-2
   - Passaro and Juhl, (2023), On the potential of mapping sea level anomalies from satellite altimetry with Random Forest Regression, *Ocean Dynamics*, 73(2), 107-116, 10.1007/s10236-023-01540-4
   - Peng et al., (2024), Analyzing the coastal sea level trends from SCMR-reprocessed altimeter data: A case study in the northern South China Sea, *Advances in Space Research*, 74(7), 2976-2992, https://doi.org/10.1016/j.asr.2024.06.036

3. **Oceanography**
    - Bolmer et al. (2022), Occlusion Sensitivity Analysis of Neural Network Architectures for Eddy Detection, *IGARSS*, 623-626
    - Bolmer et al. (2024), Estimating daily semantic segmentation maps of classified ocean eddies using sea level anomaly data from along-track altimetry, *Front. Artif. Intell.*, 7:1298283
    - Pisareva et al., (2025), Chukchi Sea circulation and Bering Strait flow reversals from reprocessed satellite altimetry, *Ocean Dynamics*, 75(3), 10.1007/s10236-025-01672-9
    - Schlembach et al., (2023), Benefits of fully focused SAR altimetry to coastal wave height estimates: A case study in the North Sea, *Remote Sensing of Environment*, 289, 113517, 10.1016/j.rse.2023.113517
    - Usoltseva et al., (2025), Effect of Coral Reefs on Wave Height Observed by Satellite Altimetry, *Remote Sensing in Earth Systems Sciences*, 10.1007/s41976-025-00228-1
4. **Inland Hydrology**
    - Chen et al. (2023), Evaluation of Sentinel-3A altimetry over Songhua river Basin, *Journal of Hydrology*, 618, 129197
    - Chen et al. (2025), Measuring Off-nadir river water levels and slopes from altimeter Fully-Focused SAR mode, *Journal of Hydrology*, 650, 132553
    - Gao et al., (2025), A multi-parameter optimized sub-waveform retracker for monitoring river water levels using SAR altimetry, *Remote Sensing of Environment*, 327, https://doi.org/10.1016/j.rse.2025.114838
    - Scherer et al., (2024), Monitoring river discharge from space: An optimization approach with uncertainty quantification for small ungauged rivers, *Remote Sensing of Environment*, 315, 114434, 10.1016/j.rse.2024.114434
    - Scherer et al., (2023), ICESat-2 river surface slope (IRIS): A global reach-scale water surface slope dataset, *Nature Scientific Data*, 10(1), 359, 10.1038/s41597-023-02215-x
5. **Sea level budget**
    - Stolzenberger et al. (2022), Simulated signatures of Greenland melting in the North Atlantic: A model comparison with Argo floats, satellite observations, and ocean reanalysis, *JGR Oceans*, 127(11), e2022JC018528
    - Willen et al. (2022), Feasibility of a global inversion for spatially resolved glacial isostatic adjustment and ice sheet mass changes proven in simulation experiments, *Journal of Geodesy*, 96(10), 75
    - Willen et al. (2024), Globally consistent estimates of high-resolution Antarctic ice mass balance and spatially resolved glacial isostatic adjustment, *The Cryosphere*, 18(2), 775-790
    - Kusche et al., (2025), Benefit of MAGIC and multi-pair quantum satellite gravity missions in Earth science applications, *Geophysical Journal International*, ggaf195
    - Müller et al., (2023), Monitoring Arctic thin ice: a comparison between CryoSat-2 SAR altimetry data and MODIS thermal-infrared imagery, *The Cryosphere*, 17(2), 809-825
6. **Coastal applications**

- Bako and Kusche (2024), Evaluation and homogenization of a marine gravity database from shipborne and satellite altimetry-derived gravity data over the coastal region of Nigeria, *J. Appl. Geodesy*, 19(2), 175–189
- Passaro et al., (2023), Coastal assessment of sentinel-6 altimetry data during the tandem phase with Jason-3, *Remote Sensing*, 15(17), 4161
- Peng et al., (2024), Assessment of Sentinel-6 SAR mode and reprocessed Jason-3 sea level measurements over global coastal oceans, *Remote Sensing of Environment*, 311, https://doi.org/10.1016/j.rse.2024.114287
- Peng et al., (2024), Wave contributions to sea levels along the coast of northern South China Sea over 2002–2022, *Advances in Space Research*, 73(9), 4584-4596, https://doi.org/10.1016/j.asr.2024.01.037
- Peng et al., (2023), A New Method to Combine Coastal Sea Surface Height Estimates from Multiple Retrackers by Using the Dijkstra Algorithm, *Remote Sensing*, 15(9), 2329, https://doi.org/10.3390/rs15092329

Report of IAS Pilot Service

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Vice-Chairs: C K Shum (USA), Jérôme Benveniste (France), and Stefano Vignudelli (Italy)

IAS Pilot Service members

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Lifeng Bao (China)
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Jean François Crétaux (France)
Xiaoli Deng (Australia), Chair
Denise Dettmering (Germany)
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Xiaoyun Wan (China)
Shengjun Zhang (China)

New Products

The following new data products have been produced by IAS Pilot Service since 2023:

- **IAS2024 coastal sea level product** (https://doi.org/10.5281/zenodo.13208305) by Peng et al., (2025). The product provides the reprocessed altimetry Jason-1/2/3 20-Hz global coastal sea level datasets.

- **A new global marine gravity model** (https://doi.org/10.5281/zenodo.12730119) by Zhang et al. (2025).
- SWOT gravity products by Sandwell et al. (2025) via link: https://topex.ucsd.edu/pub/global_grav_1min_SWOT/
- A neural network model (Harper and Sandwell, 2024) for seafloor depth prediction can be accessed through: https://doi.org/10.5281/zenodo.8029925
- OpenADB – DGFI-TUM's Open Altimeter Database (Schwatke et al., 2023). The following products are available via OpenADB: https://openadb.dgfi.tum.de/en/
  - Sea Surface Heights (SSH)
  - Sea Level Anomalies (SLA)
  - Instantaneous Dynamic Ocean Topography Profiles (iDOT)
  - Empirical Ocean Tide Model (EOT)
  - Vertical Total Electron Content (VTEC)
  - Adaptive Leading Edge Subwaveform (ALES) Retracker
- A fully automated tool JASTER (Jason Altimetry Stand-Alone Tool for Enhanced Research) to process Jason-2/3 altimetry data for water elevation time series generation over user-defined inland water body (Ross et al., 2024) are now available at the *University of Houston* (USA):
  - JASTER Altimetrisoen Feb2024 Final
  - Sentinel3 Altimetry Tool Sep 2023 V2
  - Sentinel6 Altimetry Tool Oct 2023 V2

Other products

IAS Pilot Service has included the following products that exploit or support altimetry applications:

- https://hydrostat.gis.uni-stuttgart.de/php/index.php
- https://dahiti.dgfi.tum.de/en/
- https://ipad.fas.usda.gov/cropexplorer/global_reservoir/
- https://www.hydrosheds.org/products/
- ESA Global/Coastal Sea Level/Lakes CCI (https://climate.esa.int/en/projects/sea-level/about/)
- ESA Coastal Altimetry (https://www.coastalaltimetry.org)
- NASA/NOAA PODAAC (https://podaac.jpl.nasa.gov/) Sea Level Portal
- NOAA Real-time Altimetry (https://www.star.nesdis.noaa.gov/socd/lsa/NeaRRealTime/)
- Aviso/Avisot (https://www.aviso.altimetry.fr/en/data/products/sea-surface-height-products/global/gridded-sea-level-anomalies-mean-and-climatology.html#c7273)
- Scripps global marine gravity field from satellite altimetry (https://topex.ucsd.edu/marine_grav/mar_grav.html)
- Scripps global seafloor topography from satellite altimetry (https://topex.ucsd.edu/WWW_html/mar_topo.html)
- DTU Space mean sea surface, ocean tide and marine gravity models (https://data.dtu.dk)

IAS presentations at conferences

The IAS progress, structure, and specific satellite altimetry data products have been presented and discussed with IAS Pilot Service members and altimetry scientists from all over the world at conferences, including EGU and AGU.

- **Vice-Chair Shum** presented the "IAS Pilot Services for scientific and geodetic applications" at the *30 Years of Progress in Radar Altimetry Symposium* held at the Le Corum-Place Charles de Gaulle, Montpellier, France, 2–7 Sept. 2024 (https://www.altimetry2024.org), as well as at the AGU 2024.
- IAS members attended the *45th COSPAR 2024 Scientific Assembly*, 13–21 July 2024 in Busan, Korea, (https://cospar2024.org). An oral presentation was given by Denis Deng. Discussions took place in relation to the structure of IAS Pilot Service, revision of ToR, and web services from altimetric scientists, data service stakeholders, IAG EC members including Richard Gross, as well as proposing a joint session proposal with COSPAR/IUGG/IAG at COSPAR 2026. One comment is that IAS should leverage IAS activities from that of IAG research activities, including and for example, IAG sub-commission 2.5, *Satellite Altimetry*, under Commission 2, *Satellite Gravimetry*, https://com2.iag-aig.org/sub-commission-25.

Engagement with government departments

IAS Pilot Service Chairs Shum and Deng have engaged with government departments of National Geospatial-Intelligence NGA Agency (USA), Australian Geospatial Organisation (AGO), Geoscience Australia (GA) and Intergovernmental Committee on Surveying and Mapping (ICSM, Australia) for opportunity of collaboration. An online meeting was held on 5 April 2024. Issues discussed in the meeting include altimetry for geodesy, marine gravity field and bathymetry. The requirement of IAS data products for climate change and security was also discussed.

SG 2.5.1 High-resolution altimetry for geodetic, oceanographic, cryosphere and hydrology studies (HRA)

Chair: Dr Luciana Fenoglio-Marc (Germany)
Vice-Chair: Prof Ole Baltazar Andersen (Denmark)

High-resolution altimetry for geodetic, oceanographic, cryosphere and hydrology studies (HRA) is highly connected to The Climate Change Signals in High Resolution Surface Water Observations (ICCC-HRWATER). In light of the new observations, the aim was to investigate surface water level and storage change on land and at the coast, to detect climate related signals. In the ICCC subgroup we investigate the developments allowed by high-resolution (HR) altimetry 1-D and 2-D measurements, and to encourage innovative interdisciplinary research and applications in climate change studies.

During 2023-2024 the research topic focused on producing a high-resolution water level to study hydrodynamical processes in inland and at the coast:

1. A dedicated nadir-altimeter database at 80 Hz and 140 Hz was produced over Europe with Fully Focus SAR (FFSAR) with nadir and off-nadir processing. Fenoglio et al. (in revision) show that the mean accuracy is of 15–20 cm in rivers, 8 cm in lakes, 80 cm in estuaries and 20 cm at the coast. Off-nadir processing further increases the accuracy to 6–8 cm (Chen et al., 2023, 2025). The database is available in the DETECT and 4DBalticDyn projects and will be shared with ongoing publications (Buchhaupt et al., 2025; Fenoglio et al., in preparation).
2. Validation of the SWOT cal/val phase data. These databases have been used to validate SWOT cal/val data, which confirms the higher accuracy of SWOT in inland water (Andreadis et al., 2025; Durand et al., 2023). Low-resolution (2×2 km) products at open seas and at the coast were merged in multi-mission grids (Fenoglio et al., EGU 2024). High-resolution pixel clouds, raster data, river nodes, river reaches and lake time-series in inland waters have been compared in selected test areas.
3. Combination with auxiliary data. The multi-mission altimeter data were combined with auxiliary data to derive products of geophysical parameters for rivers, lakes, coastal area and open ocean studies. Applications to inland waters quantify river discharge and surface water storage change in Central Europe (Fenoglio et al., 2025). Applications in open and coastal seas analyses improve dynamic topography and current velocities in the Baltic Sea (Fenoglio et al., 2024). A database of geophysical parameters is in preparation and will be realised in the frame of the DETECT project and in papers.

Researchers at *Wuhan University*, China, have focused on altimetry research into inland hydrology, cryosphere and sea levels:

1. **Inland Hydrology and Cryosphere.** A multi-parameter optimized sub-waveform retracker has been proposed for monitoring river and inland water levels using SAR altimetry, enhancing the water level accuracy over inland water bodies (Gao et al., 2025). Focusing on the Tibetan Plateau, a high-resolution lake water level

reconstruction algorithm was designed to provide daily water level records by fusing multisource satellite altimeters with meteorological data (Jiang et al., 2024). For the cryosphere, an improved ICESat-2 signal extraction and lead detection method was implemented to strengthen sea surface height retrieval in the Arctic and Southern Ocean (Liu et al., 2025). Meanwhile, comprehensive validation and bias analyses of ICESat-2 sea surface height products (ATL12) were conducted, contributing critical insights for cross-mission calibration and polar altimetry data integration (Sun et al., 2025a).

2. **Sea levels.** For global sea level changes, a continuous piecewise polynomial fitting algorithm with harmonics was introduced to provide better fitting results and more objective uncertainty estimation in sea level change detection (Xiao et al., 2025a). Then, multi-decadal (64-year) global sea level oscillations were identified using tide gauge data and external excitation sources explored (Xiao et al., 2025b). Moreover, the dynamic interpolation method was optimized for efficient sea surface height reconstruction from sparse altimetric datasets (Shi and Jin, 2023). For coastal extreme sea levels, a data-driven method was proposed to identify and optimize under-monitored areas in the tide gauge network, enhancing monitoring precision (Yang et al., 2024).

SG 2.5.2 Synergistic applications of satellite altimetry with other satellite sensors/physical models (SASA)

Chair: A/Prof Hyongki Lee (USA)
Vice-Chair: Chungyen Kuo (Taiwan)

The recent research led by Prof Hyongki Lee has focused on monitoring reservoir elevation changes using Jason-2/3 altimetry satellite missions. An open-source, fully automated tool JASTER (Jason Altimetry Stand-Alone Tool for Enhanced Research) has been developed to process Jason-2/3 altimetry data for water elevation time series generation over a user-defined inland water body (Ross et al., 2024). The JASTER automatically downloads data with a user's AVISO ID/PW and generates time series after specifying the spatial boundary of a water body. It utilizes the original IQR-based approach (Okeowo et al., JSTARS, 2017) + SRTM DEM + JRC's Water Occurrence maps + Hampel filter for a better performance.

Mulawarman University (UNMUL), Indonesia, initiates collaborative research with the Earth System and Global Change Group of Wageningen University and Research towards evaluation of drought and hydrological modelling for Indonesian rivers using current satellite altimetry products for inland waters. This work just started in June 2025, supported by Wageningen Institute for Environment and Climate Research (WIMEK) Graduate School through 2025 visiting research fellowship.

SG 2.5.3 High Resolution Mean Sea Surface (MSS)

Chair: David Sandwell (USA)
Vice-Chairs: Ole Andersen (Denmark) and Philippe Schaeffer (France)

Researchers since 2024 have made significant progress toward advancing the marine gravity field and bathymetry. Key accomplishments and details can be found in the section Marine gravity field and bathymetry.

SG 2.5.4 International Altimeter Service (IAS) Planning Group

Chair: C K Shum (USA)
Vice-Chair: Xiaoli Deng (Australia)

This working group is working towards from IAS Pilot Service to IAS for pooling together international resources in satellite altimetry. The IAS Pilot Service's progress and status were presented in several conferences and IAG EC meetings by C.K. Shum, Xiaoli Deng, Jérôme Benveniste, and Stefano Vignudelli during 2023 and 2025 (cf. section Report of IAS Pilot Service). Many activities can be also referred to what is presented in section Report of IAS Pilot Service. The group is calling geodetic and interdisciplinary researchers for participation in IAS.

SC 2.5 Selected publications in the period 2023 - 2025

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8 SC 2.6 Gravity Inversion and Mass Transport in the Earth System

Chair: Wei Feng (China)
Vice-Chair: Roelof Rietbroek (Netherlands)

Overview

Sub-commission 2.6 promotes and supports scientific research concerning spatial and temporal variations of gravity related to the dynamics of the Earth's interior, land surface, oceans, cryosphere, and atmosphere. A working group focusing on the geodetic observations and physical interpretations in the Tibetan Plateau has been established.

Activities during the period 2023-2025

An international Sino-European team, "*Time-Variable Gravity Field Modeling and Simulation from Present and Future Gravity Satellite Missions*", was established in 2020 under the support of the International Space Science Institute (ISSI) and ISSI-Beijing. This initiative focuses on advancing gravity field modeling and enhancing the understanding of mass transport within the Earth system, particularly in the context of the GRACE and GRACE-FO missions. The project also extends the efforts of the Combination Service for Time-variable Gravity fields (COST-G) of the IAG.

Fig. 26. Participants of the Sino-European international team meetings in Bern (26-29 June 2020) and Beijing (11-15 December 2024)

The team held two major meetings, the first one in Bern, Switzerland (26–29 June 2023), and the second in Beijing, China (11–15 December 2024). In 2025, the team released the RL02 version of the COST-G GRACE solution, a robust combination of 11 individual solutions from different international groups, i.e., Center for Space Research (CSR), German Research Centre for Geosciences (GFZ), NASA Jet Propulsion Laboratory (JPL), Astronomical Institute, University of Bern (AIUB), Centre National d'Etudes Spatiales (GRGS), Institute of Geodesy, Graz University of Technology (ITSG), Leibniz University Hannover (LUH), Innovation Academy for Precision

Measurement Science and Technology–Sun Yat-sen University (APM-SYSU), Tongji University (Tongji), Huazhong University of Science and Technology (HUST), and Southern University of Science and Technology (SUSTech). The COST-G RL02 solution demonstrates superior robustness compared to individual solutions, particularly during the early and late phases of the GRACE mission (Meyer et al., 2025). This advancement holds significant potential for improving the study of mass transport and redistribution in the Earth system, including applications in hydrology, glaciology, oceanography, and solid Earth sciences.

Additionally, two international symposiums were held successfully in Dali, China (10-12 August 2023) and Kashgar, China (15-17 August 2024), which advance our knowledge of mass transport, surface deformation, and geodynamics in Tibet. A special issue was published in Geodesy and Geodynamics for the symposium in March 2025.

Since land-ocean mass transport and fluxes are major drivers of global but also regional sea level rise these issues are now becoming part of more regional discussions of hazards and uncertainties of sea level rise (Hermans et al., 2025), and the effect of sea level rise on shore-lines and coastal erosion (Aschenneller et al., 2025).

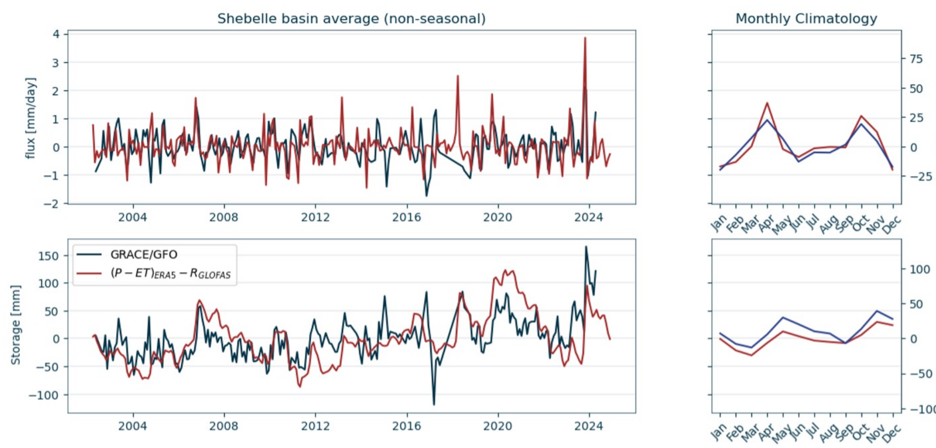

Fig. 27. Mass storage and fluxes of the Shebelle Catchment derived from GRACE/GRACE-FO and P-ET-R from ERA5 and GLOFAS output. Source: Rietbroek et al. 2025

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SG 2.6.1 Geodetic observations and physical interpretations in the Tibetan Plateau

Chair: Wenbin Shen (China)
Vice-Chair: Cheinway Hwang (China-Taipei)

Activities and publications during the period of 2023-2025

Working Group 2.6.1 concentrates on but not limit to the studies of hydrological change, crustal deformation, regional gravity field, mass migration and Moho variation, geodynamic and cryospheric processes, climate change, new techniques and methods and their applications, in Tibetan Plateau.

The 11th International Symposium on Tibet, Xinjiang and Siberia (TibXS) was held in August 2023, in Dali, Yunnan, China . In this symposium, there are about 100 participants from China, USA, Japan, Egypt, and Turkey, of which about 50 representatives presented their study achievements. Three PhD students obtained first prize awards and five PhD/Master students obtained second prize awards, for their outstanding achievements. A special issue in *Geodesy and Geodynamics* for the 11th TibXS Workshop Proceedings (Guest editors: Wei Feng, Cheinway Hwang, Wenbin Shen, CK Shum, Orhan Akyilmaz) was published with seven papers.

Fig. 28. Participants of 11th TibXS Symposium in Dali, China (10-12 August 2023)

The 12th TibXS Symposium was successfully held in August 2024, in Kashi, Xinjiang, China. In this symposium, there are about 100 participants, of which about 55 representatives presented their study achievements. The workshop encompasses a wide range of topics in geodesy and geophysics, focusing on six themes: (1) Multi-observations and interpretations over Tibet and Siberia regions; (2) Applications of time-varying gravity field; (3) Crustal deformation mechanisms and applications; (4) Satellite altimetry and applications; (5) Classical and state-of-art physical geodesy; (6) Earth and planetary dynamics.

Fig. 29. Participants of 12th TibXS Symposium in Kashgar, China (15-17 August 2024)

Publications

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5. Ding, H., Jiang, W., Luan, W., Li, J., Pan, Y., & Li, Z. (2024). The Intradecadal Periodic Signals in GPS Displacements and Their Possible Climate Change Influ-

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