International Gravity Field Service (IGFS)

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Chair: Riccardo Barzaghi (Italy)
Central Bureau Director: Georges Vergos (Greece)

IGFS website - http://igfs.topo.auth.gr/

1 Overview and Activities (2023-2025)

In the reporting period 2023-2025 the IGFS activities, given its ToR, have been managed according to the organization structure shown in Fig. 1 below.

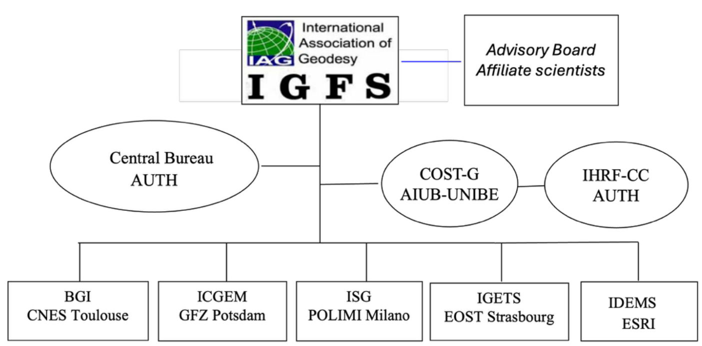

Fig. 1. IGFS Organization structure: COST-G (International Combination Service for Time-variable Gravity Fields), AIUB, Bern (CH) Central Bureau and IHRF Coordination Canter (Aristotle University of Thessaloniki), Thessaloniki (GR) BGI (Bureau Gravimetrique International), Toulouse, (F) ISG (International Service for the Geoid), POLIMI, (I) IGETS (International Geodynamics and Earth Tides Service), EOST, Strasbourg, (F) ICGEM (International Center for Global Earth Models), GFZ, Potsdam, (D) IDEMS (International Digital Elevation Model Service), ESRI, Redlands, CA (USA)

The main IGFS actions in the last two years have been focused either on the activities of its centers, namely COST-G and IHRF-CC, and to the improvements of the internal communication among the Gravity Services. Also, another fundamental part of the IGFS actions has been devoted to the connection with GGOS, Commission 2 and the United Nations Global Geodetic Centre of Excellence (UN-GGCE). In the following, these activities are documented in detail.

2 The IHRF Coordination Center

One initial objective of the Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) was the standardisation of height systems worldwide. In this way, the GGOS Focus Area Unified Height System (GGOS-FA-UHS) was established in 2010 to lead and coordinate the efforts needed towards the establishment of a global standard for the precise determination of physical heights. During the 2011-2015 term, various discussions focused on the best possible definition of a global unified vertical reference system, resulting in the IAG Resolution for the Definition and Realisation of an International Height Reference System (IHRS), which was adopted at the 2015 General Assembly of the International Union of Geodesy and Geophysics (IUGG) in Prague, Czech Republic. During the period 2015-2019, activities were undertaken to investigate the best strategy for the implementation of the IHRS; i.e., the establishment of the International Height Reference Frame (IHRF). For the period 2019-2023, the objectives of the GGOS-FA-UHS focused on (i) compiling detailed standards, conventions and guidelines to support a consistent determination of the IHRF at global, regional and national levels; (ii) coordinating with regional/national experts in gravity field modelling the computation of a first IHRF solution; and (iii) designing an operational infrastructure that will ensure the long-term sustainability and reliability of the IHRF. The focus in the current period, 2023-2025, is now put on the operational infrastructure required to ensure the maintenance and availability of the IHRS/IHRF in the future. In line with IAG practice, the development of theory and methods for the continuous improvement of the IHRS/IHRF will be continued by the IAG Commissions and the ICCT, while the operational performance will be ensured by the IAG Services, in this particular case the IGFS. With this in mind, the Central Bureau of the IGFS has developed a proposal for the establishment of a central coordinating body for the IHRF, composed of individual modules, which take care of the main components of the IHRF. The central management body is the IHRF Coordination Centre and its modules are the IHRF Reference Network Coordination, the IHRF Conventions' Coordination, the IHRF Associate Analysis Centres and the IHRF Combination Coordination.

The IHRF Coordination Centre is responsible for the general coordination of activities required for the IHRF and for the storage, publication, and servicing of the IHRF. The IHRF Reference Network Coordination implements and keeps updated a catalogue of the IHRF global reference stations, including decommissioning of destroyed stations and the addition of new stations to replace removed stations or improve the geographical distribution. The IHRF Conventions' Coordination is responsible for the maintenance of a catalogue containing the conventions and standards needed for the IHRF and should assess the impact that revisions in these conventions will have, providing the necessary theoretical and methodological updates that need to be introduced to the existing station coordinates. The IHRF Associate Analysis Centres are those national/regional agencies/bodies that contribute to the realisation of the IHRF by providing the potential values at the IHRF stations located in their countries/regions, following the conventions outlined by the IHRF Conventions Coordination and delivering detailed descriptions about their calculations. The IHRF Combination Coor-

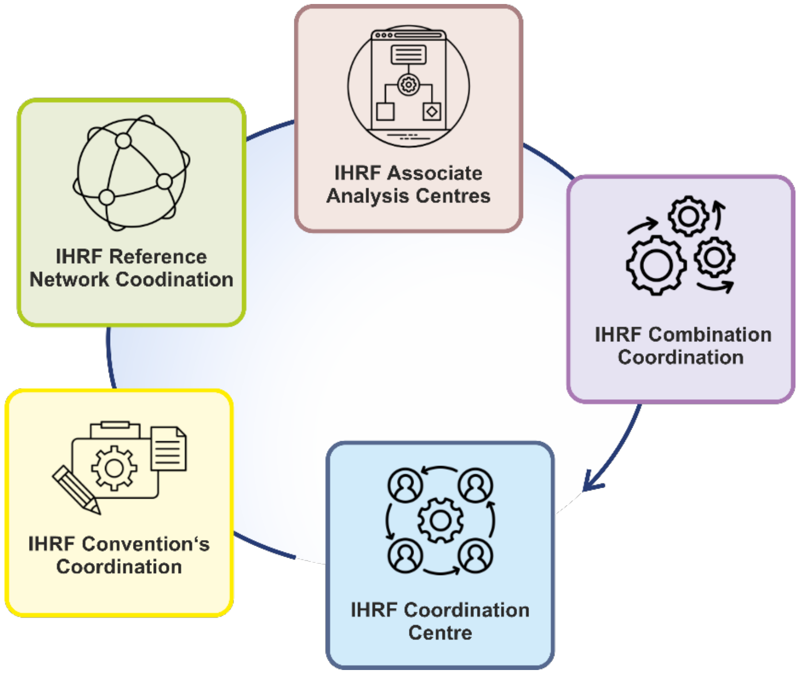

Fig. 2. Data flow between the IHRF Coordination Centre and its modules

dination is responsible for the combination and quality assessment of the regional/national solutions and for releasing the final (official) IHRF solution. The IHRF Reference Network Coordination, Conventions' Coordination, Associate Analysis Centres and Combination Coordination report to the IHRF Coordination Centre, which, in turn, reports directly to the IGFS Central Bureau.

IGFS presented this proposal to the IAG Executive Committee at its meeting on December 10, 2023, and it was unanimously approved. Thus, a new component of the IGFS dedicated to the IHRF has been born and ensures the long-term availability and reliability of the IHRF. More details on the IHRF Coordination Center based on its Terms of Reference can be found in the IHRF-CC website.

2.1 Recent activities of the IHRF Coordination Center

Since January 2023, the IHRF CC has both coordinated its managerial activities as well as participated to the organization of topical meetings and conferences. In that respect, three business meeting have been held, with two of them being held online, while the third one was carried out during the Gravity, Geoid and Height Systems 2024 conference (GGHS2024), held in Thessaloniki, Greece during September 4-6, 2024.

The "Gravity, Geoid and Height Systems 2024 Symposium" GGHS2024, co-organized by IAG Commission 2, IGFS and the Global Geodetic Observing System (GGOS), was held in Thessaloniki, Greece, from September 4-6, 2024. It focused on methods for observing, estimating and interpreting the Earth's gravity field and the essential role of gravity field modelling in measuring, understanding and predicting changes in the Earth system. Within GGHS2024 a dedicated "Session 1: Reference systems and frames in Physical Geodesy" with several presentations on the realization of the IHRF has been included.

During the reporting period, the IHRF Coordination Center has published its website (https://ihrfcc.topo.auth.gr/) where information of the scope, structure, Terms of Reference, and IHRF services are included. Furthermore, a dedicated set of simulated data has been prepared and distributed to the IHRF CC members and ASCs. The scope of these simulated data is to offer a consolidated dataset in order to experiment with current and future approaches for the determination of potential values at current and future IHRF sites. The datasets provided include terrestrial, airborne, and altimetry data, as well as satellite data from GOCE and GRACE. Finally, a dedicated documentation section has been created were the IHRF conventions have been given as well as practical guide on how to compute potential values. Finally, key publications as well as related presentation are given.

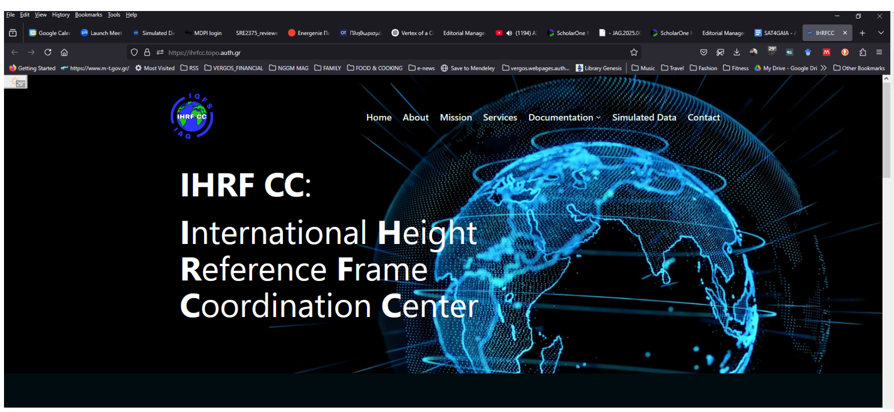

Fig. 3. The IHRF Coordination Center website

2.2 Recent activities of the IHRF Associate Analysis Centers

Germany (report by H. Denker)

The Institut für Erdmessung (IfE) at Leibniz University Hannover (LUH) continued the cooperation with Physikalisch Technische Bundesanstalt (PTB) in Braunschweig and other national metrology institutes regarding the use of optical clocks for chronometric levelling.

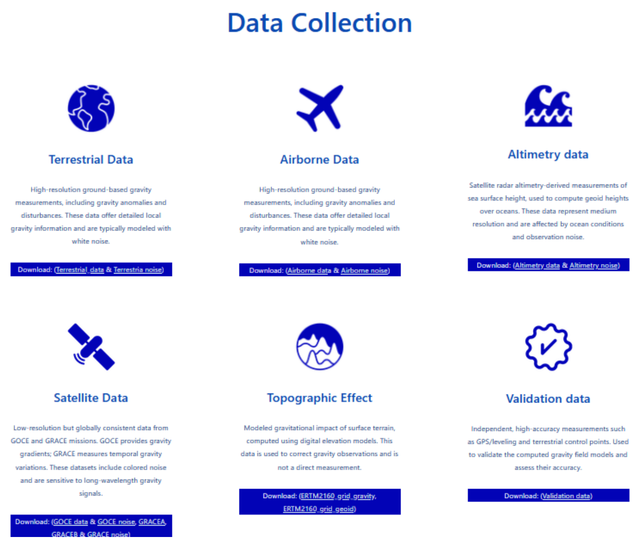

Fig. 4. Simulated data offered within the IHRF CC to experiment with methodology testing for potential determination

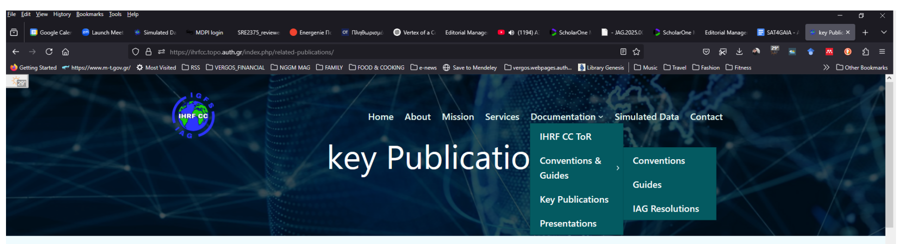

Fig. 5. The IHRF CC Documentation entries

Three recently published papers are listed below, showing that the uncertainty of chronometric levelling has reached about 4 cm with an agreement to geodetic results at a similar level.

Sweden (report by A. Alfredsson and J Ågren)

During 2023–2025, Anders Alfredsson (PhD student) and Jonas Ågren (main supervisor) conducted research on different aspects of regional and national realisation of IHRS. Both the standard GNSS/model-based realisation as well as various levelling assisted approaches were investigated in a few articles and a licentiate thesis; see the list of references below. Case studies were made over Sweden using a large part of the Baltic Levelling Ring network, a dataset of high-quality GNSS-determined ellipsoidal heights, and the Nordic/Baltic NKG2015 quasigeoid model. It is for instance concluded that including precise levelling observations in the IHRS realisation might lead to significant improvements and lower uncertainty, especially in the relative sense over short distances. It is recommended to adjust the precise levelling network with a number of GNSS/model-based geopotential numbers used as weighted “datum points” in IHRF, and to utilise variance component estimation to estimate realistic a priori uncertainties of the various data types. A careful comparison and analysis are also made with the current Swedish levelling-based height system, RH 2000. The PhD project is planned to be finalised in 2027.

South America (report by G.N. Guimarães , A.C.O.C. Matos, C. Tocho)

In South America, an experiment known as "Experiment Uruguay" was conducted to ensure that different groups were accurately calculating potential values. This experiment involved calculating the geopotential number at two stations in Uruguay, with participation from three groups – Argentina, Brazil, and Uruguay – who used the same formulas, constants, and conventions. Initially, the geoid UruGeoide110 (IGM, 2024) was utilized by these groups. Once their results converged, the groups proceeded to compute potential values at two IHRF stations: UYPT in Uruguay and AGGO in Argentina. Argentina utilized the pure gravimetric geoid version of the Geoide-Ar16 model (Piñon, 2016), Brazil employed the SAM_GEOID2023 model (Guimarães et al. 2025), and Uruguay maintained the UruGeoide110 model (IGM, 2024) model for their calculations. The results are presented in Fig. 6.

IHRF station	Difference *Geoide-Ar16* and *UruGeoide110*	Difference *Geoide-Ar16* and *SAM_GEOID2023*	Difference *UruGeoide110* and *SAM_GEOID2023*
UYPT	0.2	-0.1	-0.3
AGGO	0.2	-1.0	-1.2

Fig. 6. Geopotential values difference at UYPT and AGGO stations. Values in m^2s^{-2}.

As a result of this experiment, a guide document was created for the SIRGAS community. This documentation, available on the SIRGAS website (https://sirgas.ipgh.org/en/resources/guidelines/), outlines the formulations, constants, and conventions needed to calculate gravity potential values at an IHRF station using regional gravity field models, including pure gravity geoids and quasigeoids. The guide is based on the documentation provided on the IHRF CC website. Additionally, the document provides numerical values derived from data collected at the Uruguay station, which interested parties can use to calculate gravity potential values using their own tools and programs. They can then compare these results with those calculated by SIRGAS Working Group III. The document is available in both Spanish and Portuguese.

The Argentinean official C_p coordinates were submitted to the IHRF CC in January 2025. These values have been derived from the existing purely gravimetric geoid model, Geoide-Ar16 (Piñon, 2016) and they will be included to the first IHRF solution. Currently, several methodologies are being explored to compute a new gravimetric geoid model for Argentina, with special attention given to accurately model the complex topography of the Andes. In Gómez et al. (2024), a preliminary estimation of the Argentinean vertical datum parameter with respect to the International Height Reference Frame (IHRF) was presented using two different approaches:

- First Approach: Based on the Geodetic Boundary Value Problem (GBVP) as described by Sánchez and Sideris (2017). This method involves solving an extended version of the scalar-free GBVP following Molodensky's theory, where the vertical datum parameter is incorporated into the boundary conditions as an additional unknown.

- Second Approach: Combines geopotential numbers derived from leveling and gravity data with those obtained from a quasigeoid model.

Both methods require GNSS/leveling data and a high-precision gravimetric quasigeoid model. The estimation results with the first and second approach were $0.46 \pm 1.78\ m^2s^{-2}$ and $0.46 \pm 1.37\ m^2s^{-2}$, respectively. The vertical datum parameter can be further used to integrate SRVN16 into the IHRF. The results agree with the previous estimation of Tocho and Vergos (2015) but show differences with the one made by Sánchez and Sideris (2017) so for this discrepancy further studies are necessary in Argentina and South America.

The Brazilian official C_p coordinates were submitted to the IHRF CC in February 2025. The values were obtained from the South American Gravimetric Geoid (SAM_GEOID2023). The model was computed using the Meissl-modified Stokes kernel, which was implemented in the SHGeo software package developed by the University of New Brunswick, Canada. National geoid and quasi-geoid models from Colombia and Uruguay were also computed in 2024 and employed to obtain potential values in MEDE and UYPT stations, respectively.

A paper about the IHRF CC was published by Dr. Claudia Tocho in the GEOMAIL-BLOG, a key communication platform in Latin America for advancements in geodesy. It can be downloaded at: IHRF CC geomailblog

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3 The International Combination Service for Time-variable Gravity Fields – COST-G

The Combination Service for Time-variable Gravity fields (COST-G) has continued its work as a product center of the International Gravity Field Service (IGFS) of the IAG. In the frame of the Horizon2020 project Global Gravity-based Groundwater Product (G3P) the weighting scheme for the combination of the monthly GRACE-FO gravity fields was revised and consequently a second release of COST-G GRACE-FO combinations released in 2023, which since then has been continued operationally (Meyer et al, 2024). For quality control, COST-G performs a comparison of the signal content of the individual contributions to avoid introducing biases by the inclusion of regularized solutions with attenuated signal strength in the combination, and noise assessment of the individual contributions and the combination for validation purpose (Fig. 7). COST-G has assisted the product updates RL06.1, ... RL06.3 of the GRACE-FO Science Data System (SDS) Analysis Centers CSR, GFZ and JPL by its quality control and test combinations. Meanwhile the RL06.3 solutions are routinely incorporated in the operational combination.

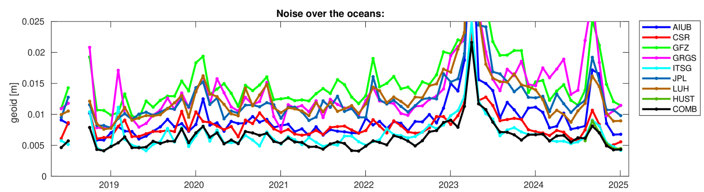

Fig. 7. Noise assessment of the operational COST-G GRACE-FO RL02 monthly combinations.

The relative weights of the combination are computed by variance component estimation on solution level (Fig. 8) and are in good agreement with the noise assessment. Since the autumn of 2024 the monthly GRACE-FO solutions of HUST are taken into account as a new high-quality contribution to the operational combination, with a marked influence on the relative weights. Currently the inclusion of the Tongji monthly solutions is under discussion. Tongji provides another high-quality, low-noise solution, but tests of the signal strength have revealed a slight offset in the ice mass trends on the central ice shield of Greenland which currently is under investigation.

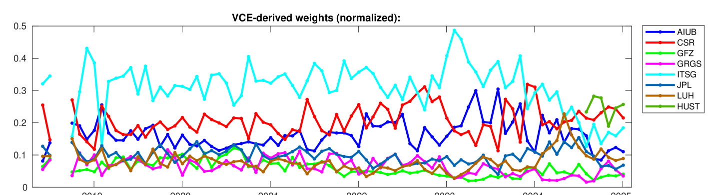

Fig. 8. Relative weights of the operational COST-G GRACE-FO RL02 monthly combinations.

Since spring 2023 COST-G provides a Fitted Signal Model (FSM; Peter et al., 2022), which consists of a constant, a linear trend and seasonal variations with annual and semi-annual period per gravity field coefficient, adjusted to the time-series of monthly GRACE-FO combined gravity fields as another product for the purpose of operational precise orbit determination (POD) of Low Earth Orbiters (LEOs). The COST-G FSM is updated quarterly with the newest monthly GRACE-FO combinations. The latest achievement of COST-G has been the recombination of the GRACE monthly gravity fields applying the same updated weighting scheme as is used for the GRACE-FO RL02 combination. The new COST-G GRACE RL02 does not only facilitate the use with the consistently combined operational COST-G GRACE-FO RL02, but also contains updates of the AIUB and GRGS time-series and as addidional contributions the solutions of LUH, and of the new COST-G ACs from

China APM-SYSU, HUST, SUSTech, and Tongji (Fig. 9). With 11 ACs COST-G is meanwhile more broadly based than the International GNSS Service (IGS), archetype of the IAG services.

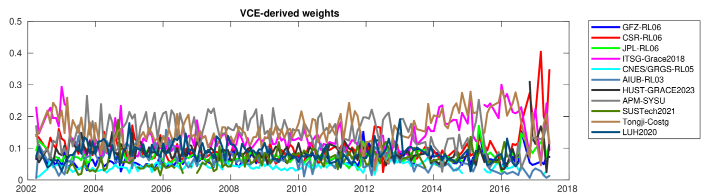

Fig. 9. Relative weights of COST-G GRACE RL02 combination.

The new COST-G GRACE RL02 has been presented at the EGU 2025 (Meyer et al., 2025) and the level-2 products (spherical harmonic coeffcients) were available just in time for the EGU at the International Center for Global Earth Models (ICGEM). The corresponding Level-2b (augmented and post-processed spherical harmonic coefficients) and Level-3 (global grids derived from the Level-2b shperical harmonic coefficients and time-series of mass change for selected river and glacial basins with added uncertainty infromation) products are currently generated at the COST-G Level-3 Product Center GFZ and will be made available at the Gravity Information Service (GravIS).

The COST-G GRACE RL02 has been successfully validated by the COST-G Validation Center at TUD, improvements with respect to RL01 are mainly visible for small basins and during the early and late mission phase of GRACE when instrument problems and high solar activity made the data analysis challenging and the COST-G combination profits most from the broader data basis of 11 ACs contributing to the new combination (Fig. 10).

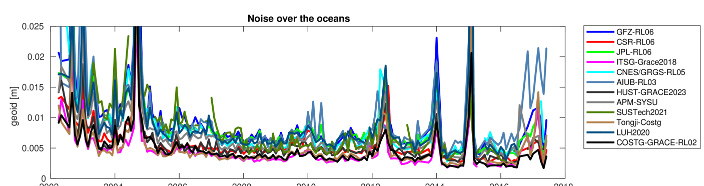

Fig. 10. Noise assessment for the COST-G GRACE RL02 combination

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4 Joint activities with Gravity Services, Commission2, GGOS and UN-GGCE

4.1 Schools on geoid computations and height systems

ISG in cooperation with IGFS, organized the following two schools:

- *The 14th International School on "The Determination and Use of the Geoid"*
  The 14th School has been organized in Buenos Aires (Argentina), on November 13th-17th, 2023. It was held at the National Geographic Institute of Argentina. It was organized in cooperation with ISG, SIRGAS (Geocentric Reference System for the Americas), IGN (Instituto Geográfico Nacional de la República Argentina), the Instituto Panamericano de Geografía e Historia, Universidade Federal de Uberlândia, Universidad Nacional de La Plata), with financing from the project of the Pan American Institute of Geography and History (PAIGH): “SIRGAS2023: Geodetic Reference Framework for the Sustainable Development of the Americas”, the National Geographic Institute, and IAG. The five lectures were given by R. Barzaghi, N. Pavlis, R. Forsbeg and L. Sancez. 40 participants attended this school, mainly from South America countries (https://www.isgeoid.polimi.it/Schools/schools_arch.html).
- *The 15th International School on "The Determination and Use of the Geoid"*
  The 15th School took place in Almaty (Kazakhstan), on April 7th-11th, 2025. It was organized by the Institute of Ionosphere, in cooperation with ISG. This edition represented a landmark achievement, being the first occurrence of the School in Central Asia. The school was specifically designed to train graduate students, early-career researchers, and specialists from national geodetic agencies and academic institutions in the determination and application of gravimetric geoids for a broad spectrum of scientific and technical geodetic applications. The five lectures were given by R. Barzaghi, A. Jäggi, R. Forsbeg and L. Sancez. 32 participants attended this school from Kazakhstan and surrounding countries (https://www.isgeoid.polimi.it/Schools/schools_arch.html).

4.2 The Gravity Geoid and Height Systems 2024 Symposium

The joint IAG Commission 2, IGFS and GGOS Symposium – GGHS2024 was held in Thessaloniki (Greece), on September 4th-6th, 2024. It has been hosted in the premises of the

Aristotle University of Thessaloniki Research Dissemination Center (KEDEA). It focused on methods for observing, estimating and interpreting the Earth's gravity field and the essential role of gravity field modelling in measuring, understanding and predicting changes in the Earth system. The scientific program was organized on six sessions, namely:
Session 1: Reference systems and frames in Physical Geodesy
Session 2: Novel technologies in terrestrial, airborne and satellite gravity field determination
Session 3: Static and time-variable global gravity field modelling
Session 4: Regional gravity field modelling and geophysical interpretation
Session 5: Gravity for climate, atmosphere, ocean and natural hazard research
Section 6: Data management, dissemination of results and networking of stakeholders.
130 participants from 26 countries attended the conference.

4.3 The GEOMED2 project

The GEOMED2 Project that started in 2015 has been proposed by IGFS in cooperation with BGI, ICGEM, ISG. This project aims at estimating a high-resolution geoid in the Mediterranean area based on local gravity data, the most recent Global Geopotential Models and an ad hoc DTM/bathymetry model. Both stochastic and spectral methods for the determination of the geoid and the rigorous combination of heterogeneous data are applied. The new geoid estimates will then be used to obtain an updated estimate of the Mean Dynamic Sea Surface Topography over the whole Mediterranean Sea. Further activities are planned in view of the next IAG General Assembly in Rimini (Italy), on September 1st-5th, 2025.

4.4 JWG/JSG

In the period 2023-2025, IGFS has also participated in the activities of the following JWG/JSG, namely:

- JWG2.2.1: Comprehensive gravity data integration for the sub-cm geoid/quasi-geoid modelling
- JSG T.47: Height datum: Definition, New Concepts, and Standardization
- JWG 2.1.1: Development of the International Terrestrial Gravity Reference Frame

4.5 GGOS and UN-GGCE

In the last two years, IGFS contributed to keeping the link between the Gravity Services and GGOS. Particularly, this has been done via the participation of IGFS into the IHRS/IHRF project and in the definition of the Global Geodetic Reference System/Frame (GGRS/GGRS) which aims at defining the new global gravity reference system that will replace IGSN71.

Furthermore, IGFS has been involved in the activities of the United Nations Global Geodetic Centre of Excellence (UN-GGCE). This in support of the actions for implementing the General Assembly Resolution 69/266 'A Global Geodetic Reference Frame for Sustainable Development', particularly in all the main aspects that refers to gravity (e.g. time variable gravity changes, IHRS/IHRF and sea level changes).