Journal of Geodesy (2023) 97:59
https://doi.org/10.1007/s00190-023-01758-6

EDITORIAL

Towards an integrated global geodetic reference frame: preface to the special issue on reference systems in physical geodesy

Laura Sánchez[1] · Hartmut Wziontek[2] · Yan Ming Wang[3] · George Vergos[4] · Ludger Timmen[5]

Published online: 20 June 2023

Already in 1878 Bruns noted in his famous work *Die Figur der Erde* (Bruns 1878) that an ellipsoid of revolution would most likely not be sufficient to characterise the figure of the Earth. At that time, he referred to the results of arc measurements, while today, technology has advanced enormously and space geodesy allows positioning and determination of the sea surface below the cm-level almost globally and to describe the Earth's surface in very detail. However, important physical properties, i.e. related to the question in what direction the water flows, are incomplete without considering the Earth's gravity field. Heights with a physical meaning refer to equipotential surfaces of the Earth gravity potential, which cannot be measured directly. Future optical clock comparisons may enable the determination of geopotential differences with superior accuracy, but these point measurements will need to be densified and linked to a global height reference. Therefore, the geopotential has still to be inferred from its gradient, the acceleration of gravity, or even its second derivative, or from satellite orbit perturbations. Although satellite gravity field missions like GOCE and GRACE have marked a breakthrough in the determination of the geopotential field and its temporal changes, only terrestrial gravity observations enable for inferring highest spatial and temporal resolution. State-of-the-art absolute gravimeters provide an uncertainty of a few parts per billions and by this, they are sensitive to mass redistributions and vertical displacements.

Monitoring of the Earth system is a central element of the Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) (Plag and Pearlman 2009). While the definition, implementation, maintenance and widespread use of the International Celestial and Terrestrial Reference Systems (ICRS, ITRS) provide a high-precision and globally consistent geometric reference frame, the establishment of equivalent global physical reference systems that support the reliable quantification of changes related to the Earth's gravity field, such as sea level variations, mass displacements, processes related to geophysical fluids, is a current main goal of the international geodetic community. This is reflected by the IAG resolutions No. 1 and 2 adopted during the General Assembly of the International Union of Geodesy and Geophysics (IUGG) 2015 in Prague: for the definition and realisation of an *International Height Reference System* (IHRS), and for the establishment of a *Global absolute gravity reference system* (Drewes et al. 2016). This special issue of the Journal of Geodesy on *Reference Systems in Physical Geodesy* contains 18 papers devoted to the implementation of the IHRS and the proposed new international gravity reference frame.

In the case of the IHRS, it is defined as a gravity potential-based reference system (Ihde et al. 2017): the vertical coordinates are geopotential numbers referring to an equipotential surface of Earth's gravity field realised by the IAG conventional value W_0 (Sánchez et al. 2016), whereas

✉ Laura Sánchez
lm.sanchez@tum.de

Hartmut Wziontek
hartmut.wziontek@bkg.bund.de

Yan Ming Wang
Yan.Wang@noaa.gov

George Vergos
vergos@topo.auth.gr

Ludger Timmen
timmen@ife.uni-hannover.de

1 Deutsches Geodätisches Forschungsinstitut (DGFI-TUM), Technical University of Munich, Arcisstr. 21, 80333 Munich, Germany

2 Federal Agency for Cartography and Geodesy (BKG), Karl-Rothe-Str. 10-14, 04105 Leipzig, Germany

3 National Geodetic Survey (NGS), National Oceanic and Atmospheric Administration (NOAA), 1315 East-West Highway, Silver Spring, MD 20910-3282, USA

4 Department of Geodesy and Surveying, Laboratory of Gravity Field Research and Applications, Aristotle University of Thessaloniki, University Box 440, 54124 Thessaloniki, Greece

5 Fakultät für Bauingenieurwesen und Geodäsie, Institut für Erdmessung, Leibniz Universität Hannover, Schneiderberg 50, 30167 Hannover, Germany

the spatial reference is given by the ITRF (*International Terrestrial Reference Frame*) coordinates. The realisation of the IHRS is the *International Height Reference Frame* (IHRF): a global reference network with precise geopotential numbers referring to the IHRS. As the geopotential reference value is constant and conventionally adopted, the main challenge in the establishment of the IHRF is the determination of the potential values with realistic uncertainties.

Supported by a strong international cooperation, Sánchez et al. (2021) describe the most recent efforts for the computation and accuracy assessment of potential values based on global gravity models of high resolution, different methods for regional gravity field modelling (geoid computation), and the vertical datum unification of the existing physical height systems into the IHRS/IHRF (for the latter, see also Sánchez and Sideris 2017). As the gravity potential can be determined by numerical integration methods using spatially distributed gravity values, finite resolution of the datasets and different approaches developed over the centuries may lead to discrepancies, although the potential itself should be unique. In this context, a cornerstone in our understanding of the consistency of contemporary methods has been the successful completion of the so-called *Colorado experiment*. Within this experiment, 14 groups worldwide computed geoid undulations, height anomalies, and potential values in a region of about 730 km $\times$ 560 km with height variations up to 3000 m in Colorado (USA). All the groups employed the same gravity and topography input datasets provided by US National Geodetic Survey (NGS), but different modelling strategies. The 14 solutions represent the state-of-the-art in precise gravity field modelling of high resolution and the results of this experiment provide a benchmark in the evaluation of regional gravity field modelling methods. Wang et al. (2021) summarises objectives, configuration, and results of the Colorado experiment.

The evaluation of the 14 individual solutions is based on the comparison with each other and with a high precise GNSS/levelling dataset of the *Geoid Slope Validation Survey 2017* (GSVS17), which were not known to the geoid developers. Seven of the 14 solutions are published in this special issue. Willberg et al. (2020) applied the method of residual least squares collocation to combine the terrestrial and airborne gravity data smoothed by a Gaussian low-pass filter. Their model shows the lowest standard deviation to the reference. They demonstrate that assigning different weights to the terrestrial and airborne gravity datasets in the combination cause a few cm geoid differences. Işık et al. (2021) computed various geoid models using the least squares modifications of Stokes and Hotine integral formulas with additive corrections. The computations using each formula were carried out considering different solutions based on terrestrial-only, airborne-only and combined gravity datasets. The results using the combined data present an accuracy of 2.7 cm for the Hotine method and 2.9 cm for the Stokes method when compared with the GNSS/levelling reference data. Grigoriadis et al. (2021) used the least square collocation and spherical FFT methods in geoid computation. The estimated geoid accuracies are in the range of 2 to 3 cm, which are consistent with the geoid differences between the GSVS17 GNSS/levelling data and the models. Claessens and Filmer (2020) applied the *AUSGeoid approach*, which is based on the remove-compute-restore method and deterministic modifications of the Stokes kernel. They tested various approaches for data gridding, terrain correction computation, and land and airborne data combination, reaching a standard deviation of the differences with the GNSS/levelling data at the 4.3 cm level. Liu et al. (2020) employed the remove-compute-restore approach using spherical radial basis functions (SRBF) to determine quasi-geoid heights, investigating various types of SRBFs and contributing factors to their proper application in geoid modelling. The accuracies reached with respect to the available GNSS/levelling data were at the 2.9 cm level, while the RMS difference value with respect to the mean geoid of the 14 solutions was 1.6 cm. Wang et al. (2020) employed the remove-compute-restore approach and followed Molodensky's approach to determine the quasi-geoid, while the final geoid was obtained by evaluating the quasi-geoid to geoid separation with Bouguer anomalies. The final computed geoid presents differences with the GNSS/levelling data at the 5 cm level. Varga et al. (2021) determined the geoid using the least-squares modification of Stokes' formula with additive corrections method. The comparison with the GNSS/levelling shows an accuracy improvement around 1.1 cm or 20% in terms of standard deviation when airborne and terrestrial gravity data are used, compared to the geoid model computed only from terrestrial gravity data.

When evaluating the aforementioned geoid solutions to the independent GSVS17 GNSS/levelling data, following accuracies (in terms of standard deviations of the differences) of the final geoid models were found: 2.9 cm (Willberg et al. 2020), 3.4 cm (Işık et al. 2021), 2.5 cm (Grigoriadis et al. 2021), 3.2 cm (Classens and Filmer 2020), 2.9 cm (Liu et al. 2020), 2.5 cm (Wang et al. 2020) and 3.5 cm (Varga et al. 2021). These values show that all methods and processing approaches provide results that agree to each other at the 1 cm level. Wang et al. (2021) summarise a detailed comparison of the 14 solutions that contributed to the Colorado experiment. Van Westrum et al. (2021) provide a detailed description of the measurement and data analysis of the reference GNSS/levelling validation data along the GSVS17 profile. The input gravity and topographic data, the GNSS/levelling validation data, and the 14 geoid and quasi-geoid models produced within the Colorado experiment are available from the *International Service for the*

Geoid[1] (Reguzzoni et al. 2021) and can be used as a basis to evaluate any geoid computation method or software anywhere.

Based on the results of the Colorado experiment, Sánchez et al. (2021) present a detailed roadmap for the realisation of the IHRS, including:

- Strategy for the determination and evaluation of IHRF coordinates depending on the data availability (especially surface gravity data and topography models),
- Strategy to improve the input data required for the determination of IHRF coordinates,
- Strategy for the IHRF implementation at the regional and national level,
- Strategy to ensure the usability and long-term sustainability of the IHRF.

Another important contribution to this special issue is about the appropriate handling of permanent yielding of the Earth due to tides in the determination of potential values and geoid modelling by Mäkinen (2021).

Based on Sánchez et al. (2021), a current international action with the contribution of more than 50 colleagues concentrates on the computation of IHRF coordinates at the reference stations selected for the IHRF reference frame.

A new gravity reference system and frame is proposed by Wziontek et al. (2021), which meets the accuracy of state-of-the-art terrestrial gravimetry and fulfil the requirements in monitoring global changes in the Earth system. It supports applications in metrology and satellite geodesy and is intended to replace the previous International Gravity Standardisation Net 1971 (IGSN71, Morelli et al. 1974). The new system is based on the instantaneous acceleration of free-fall, expressed in the International System of Units (SI), and a set of conventional corrections for the time-independent components of gravity effects to ensure long-term stability. The frame as the system's realisation includes a set of conventional temporal gravity corrections which represent a uniform set of minimum requirements. Traceable measurements with absolute gravimeters (AG) provide the basis of the frame, since they allow for a realisation of this system anywhere at any time without the need in classical geodetic observation networks. The traceability of AGs is ensured by comparisons and monitoring at reference stations. A global set of stations observed by AGs provides absolute gravity values at the microgal[2] level and is meant to provide the backbone of the frame. Core stations with at least one available space geodetic technique will provide a link to the terrestrial reference frame. The proposal is a great step forward in terrestrial gravimetry for geoscientific applications on regional to global scale.

In early 2022, an unfortunate coincidence of the chosen acronym IGRF for the *International Gravity Reference Frame* was brought to attention. This acronym is already used by IAGA for the *International Geomagnetic Reference Field* since the 1960th. To avoid confusion within IUGG, both, name and acronym, were changed to *International Terrestrial Gravity Reference System/Frame*, ITGRS/ITGRF. Therefore, the terms used in Wziontek et al. (2021) need to be updated in future use. Specifically, the IGRS conventions 2020, which cover substantial corrections for temporal gravity changes should now be referred to the ITGRS.

International absolute gravimeter comparisons are a key component for the realisation of the proposed ITGRS. Pálinkáš et al. (2021) delineate their importance and describe in detail an approach for a consistent evaluation. By considering correlations between measurements, realistic uncertainty estimates are derived by strict error propagation, and the detection and the treatment of outliers is discussed. They reprocess key comparisons which have been successfully performed since 2009 and compare with solutions allowing all participating AGs to contribute to the absolute datum level of the comparison reference values and not only the instruments operated by National Metrological Institutions or their Designated Institutes. Monitoring of AGs at reference stations is another key component of the proposed ITGRF. Antokoletz et al. (2020) describe temporal gravity variations at the Argentinean-German Geodetic Observatory (AGGO) by co-location of superconducting and absolute gravimeters to serve as a reference function. As fundamental geodetic observatory in the Global Geodetic Observation System—GGOS, AGGO provides a link to the ITRF. Together with the excellently characterised gravity time series, it fulfils the requirements to become the first core station of ITGRF in South America. A detailed assessment of the stability of AGs and long-term gravity trends is given by Scherneck et al. (2020) based on the combination of the time series of a superconducting gravimeter (SG) at Onsala, Sweden and repeated AG observations over 10 years, including one of the first measurements with a quantum gravimeter. They infer from a multi-campaign adjustment the SG scale factor and AG deviations simultaneously, obtaining residuals at the 5 nm/s^2 RMS level. The documented systematic changes in the AGs contribute to a more robust estimate of secular change of gravity dominated by glacial isostatic adjustment (GIA) in the Baltic Shield area with AGs.

The study of GIA effects in Fennoscandia with AGs is further addressed by two contributions. The extensive work of Bilker et al. (2021) covering a period of more than 40 years impressively shows the potential of AGs to independently

[1] https://www.isgeoid.polimi.it/Projects/colorado_experiment.html.

[2] $1 \mu\text{Gal} = 10^{-8}$ m s^{-2}

confirm land uplift models. A systematic offset for the JILAg-5 instrument operated in Finland was estimated. Considering deviations documented by international comparisons of AG considerably improved trends of seven stations, giving gravity to height change ratios in the range of − 0.21 µGal/mm. A similar study for Estonia by Oja et al. (2021), although with a distinct shorter time basis, documents the capabilities as well, but show also the limits of such an approach. Both studies proof the great potential of precise absolute gravity observations to quantify long-term changes but also the need in a careful monitoring of AGs, as proposed for the upcoming ITGRF. Finally, Schilling et al. (2020) present a local gravity field model for a very long baseline atom interferometer with a 10-m-long interaction zone under construction at the Leibniz University Hannover. This detailed investigation is the basis to transfer its measurement results to other AGs. The need in the application of such a high-level absolute gravity reference is motivated by deviations of AGs from decades of international comparisons. Because there is no natural gravity reference, a common reference level must be derived by all AGs participating in such comparisons. The availability of a high precision quantum gravimeter based on a completely independent technology provides the potential to establish a gravity datum with high temporal stability—and by this has a great potential for the ITGRF, too.

The work presented in this special issue has been made possible by a strong international collaboration coordinated within the IAG. The IHRS implementation and the comparison of geoid modelling approaches were coordinated by the *Focus Area Unified Height System* of the *Global Geodetic Observing System* (GGOS) and its working group 0.1.2: *Strategy for the realisation of the IHRS* (Sánchez 2019; Sánchez and Barzaghi 2020); the IAG Sub-commission 2.2: *Methodology for geoid and physical height systems* (Ågren and Ellmann 2019); the joint working group 2.2.2: *The 1 cm geoid experiment in Colorado* (Wang and Forsberg 2019); and the study group 0.15: *Regional geoid/quasi-geoid modelling—Theoretical framework for the sub-centimetre accuracy* of the IAG Inter-Commission Committee on Theory—ICCT (Huang and Wang 2019). The proposals for the definition of the ITGRS and its realisation, the ITGRF, are a result of lively exchange and discussions within the IAG joint working group 2.1.1: *Establishment of the International Gravity Reference Frame*. This support from the geodetic community is greatly valued.

With the 18 papers in this special issue, important issues related to the establishment of the IHRF and ITGRF as well as to the improvement of accurate geoid modelling and the long-term stability of absolute gravity observations have been addressed. We are grateful to all authors for the efforts. A large number of international colleagues served as reviewers for the manuscripts, a laborious and time-consuming task. We thank them all for their important and diligent work. Finally, we would like to thank the Editor-in-Chief, Jürgen Kusche, for his generous and indispensable support in the editorial process, from the development of the special issue to its final publication.

Funding Open Access funding enabled and organized by Projekt DEAL.

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