Inter-Commission Committee on Theory (ICCT)

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1 Structure

Joint Study Groups

JSG T.38 Exploring the similarities and dissimilarities among different geoid/quasigeoid modelling techniques in view of cm-precise and cm-accurate geoid/quasigeoid
Chair: Ropesh Goyal (India)
Vice-Chair: Sten Claessens (Australia)
Affiliations: Commission 2, IGFS

JSG T.39 Gravitational field modelling and analysis for oblate and prolate planetary bodies
Chair: Michal Šprlák (Czech Republic)
Affiliations: Commission 2, ICGEM

JSG T.40 Modelling the gravity field of irregularly shaped celestial bodies
Chair: Zhi Yin (China)
Affiliations: Commissions 1,2, IGFS

JSG T.41 Geodetic quality/integrity modelling, monitoring and design
Chair: Safoora Zaminpardaz (Australia)
Affiliations: Commissions 1,2,3,4

JSG T.42 Theoretical developments and applications of combined methods for a better understanding of the Earth's lithospheric formation, structure, and dynamics
Chair: Robert Tenzer (China-Hong Kong)
Affiliations: Commissions 2,3

JSG T.43 Statistical methods in regional gravity field modelling
Chair: Mehdi Eshagh (Czech Republic)
Affiliations: Commissions 1,2, IGFS

JSG T.44 Atmospheric coupling studies
Chair: Andres Calabia Aibar (Spain)
Vice-Chair: Binod Adhikari (Nepal)
Affiliations: Commission 4, GGOS (GSWR)

JSG T.45 Dynamic gravity modelling of given distributions
Chair: Dimitrios Tsoulis (Greece)
Affiliations: Commissions 2,3

JSG T.46 Deformation, rotation and gravity field modeling for Earth and space
Chair: Yoshiyuki Tanaka (Japan)
Affiliations: Commissions 2,3

JSG T.47 Height datum: Definition, New Concepts, and Standardization
Chair: Xiaopeng Li (USA)
Vice-Chair: Marcelo Santos (Canada)
Affiliations: Commission 2, IGFS

JSG T.48 Theoretical Foundations of Machine and Deep Learning in Geodesy
Chair: Lotfi Massarweh (The Netherlands)
Vice-chair: Mostafa Kiani Shahvandi (Switzerland)
Affiliations: Commissions 2,3,4, GGOS (AI4G)

JSG T.49 High-resolution probing of the troposphere and ionosphere
Chair: Michela Ravanelli (Italy)
Affiliations: Commission 4, GGOS (Geohazards Monitoring, GSWR)

JSG T.50 High-precision GNSS theory and algorithms
Chair: Dimitrios Psychas (The Netherlands)
Affiliations: Commissions 1,4

2 Activities during the reporting period 2023-2025

JSG T.38: Exploring the similarities and dissimilarities among different geoid/quasigeoid modelling techniques in view of cm-precise and cm-accurate geoid/quasigeoid

Chair: Ropesh Goyal (India)
Vice-Chair: Sten Claessens (Australia)
Affiliations: Commission 2, IGFS

Members:
Ismael Foroughi (Canada)
Jonas Ågren (Sweden)
Xiaopeng Li (USA)
Bihter Erol (Turkey)
Pavel Novák (Czech Republic)
Koji Matsuo (Japan)
Riccardo Barzaghi (Italy)
Michal Šprlák (Czech Republic)
Jianliang Huang (Canada)
Yan-Ming Wang (USA)
Cheinway Hwang (China-Taipei)
Neda Darbeheshti (Australia)

Associate member:
Jack McCubbine (Australia)

Activities of the group

Members of the group undertook significant studies that contributed to the objectives of the study group and highlighted the requirement of continued theoretical and applied studies in this domain. Members not only pursued computation of cm-precise or cm-accurate geoid and quasigeoid, but studies were undertaken to analyse different components which present possible challenges of constructing a cm-precise/accurate geoid and quasigeoid. Members of the group focused on mutual cooperation and undertook various activities including but not limited to publishing papers in journals, presenting their findings in key conferences, organising workshops, attracting sponsored projects from respective government funding agencies, recognitions for their contributions, and significant interaction with other IAG groups.

Achievements and Results

Studies

Most of the work during the period 2023-2025 focuses on the following three out of five objectives of the JSG:

- Study and quantify the differences in handling the topography, atmosphere, ellipsoidal correction, and downward continuation in different geoid/quasigeoid modelling methods
- Study, quantify and reduce the assumptions and approximations in different geoid modelling methods to attain congruency within some threshold
- Study the requirement for merging various components/steps of different geoid modelling methods

The studies suggest that there still are various factors to be considered for achieving cm-precise or cm-accurate geoid/quasigeoid. Cheinway Hwang and group focused on assessing the challenges of constructing a cm-accurate geoid model over Taiwan, a region with complex topography and active crustal dynamics. The discrepancies between gravimetric and observed geoidal heights derived from GNSS/leveling data are evaluated, which are essential inputs to hybrid geoid models. Their study showed significant errors caused by vertical land motion, temporal mismatches in measurement epochs, and inconsistencies among different geodetic reference frames. The work highlights the need for standardizing reference frames and applying velocity field corrections to GNSS/leveling data before hybrid geoid construction.

Barzaghi and group estimated the new Italian geoid by using collocation and 1D-FFT reaching a 3 cm precision with both methods w.r.t. GNSS/levelling. Particularly, a method for using collocation in a windowed mode was setup. Only gravity data around the computation point are selected according to the correlation length of the covariance function of the gravity residuals. Furthermore, they now plan to use a dynamic crustal deformation model over Italy to align in time, GNSS and levelling observations. This would help in assessing the geoid precision. Testing the RBF approach for gravity field approximation and geoid computation over Italy will also be undertaken.

The published studies by the group members related to the objectives of this JSG include Foroughi et al. (2023a) who discussed in detail the data requirements for the determination of a sub-centimeter geoid. Marotta et al. (2024) investigated the effects of different parameters (mass density, topographic models, geopotential models, and stokes kernel modifications) on geoid modeling accuracy. Abbak et al. (2025) investigated combined effects of two terrain corrections and three deterministic modifiers on the Stokes-Helmert geoid over Konya, Turkey. Foroughi et al. (2023b) analysed the uncertainties of the topographical density variations in view of a sub-centimetre geoid. Erol et al. (2023) studied the accuracy assessment of the SRTM2gravity high-resolution topographic gravity model in geoid computation and Karaca et al. (2024) assessed various gravity gridding techniques and the impact on geoid model accuracy. Yang et al. (2023) reviewed and compared the expressions of harmonic correction for RTM corrections to gravity anomaly and height anomaly with various methods, i.e. the condensation method, the regularized downward continuation method of TS, the regularized downward continuation method of SH, the complete method, and the Kadlec's method. Udama et al. (2024) analyses different combinations of heterogenous gravity data for determining geoid over Bali and studying the consistency of precision among the developed geoid models.

Sansò, et al. (2023) studied the two equivalent geodetic approaches (Molodensky's and Helmert's Theories) for determining the Gravity Potential and the Earth Surface at centimetric level. Goyal et al. (2023a, 2023c) investigated the congruence between gravimetric geoid models over India to analyse regional and national consistency in developed geoid model using three different geoid modelling methods. Foroughi et al. (2023c, 2023d) meticulously studied the power of airborne vector gravimetry for more accurate geoid models while optimising the flight line spacing. Šprlák and Pitoňák (2024) discussed Far-Zone effects for spherical integral transformations and provided detailed formulas for the radial boundary value problem and its derivatives while Pitoňák et al. (2024a, 2024b, 2025) developed a Matlab based software for this study. Pitoňák et al. (2023a, 2023b) estimated height anomalies from gradients of the gravitational potential using a spectral combination method.

Different methods compute either geoid or quasigeoid as primary product (except LSMSAC, that gives both geoid and quasigeoid as primary product depending on handling the topographic and downward continuation effect) and hence, geoid-quasigeoid term plays a significant role for determining congruency within the geoid/quasigeoid modelling techniques. Wang et al. (2023) calculated geoid-quasigeoid separation (GQS) by including corrections due to potential, gravity gradient, and gravity difference and presented a case study over Colorado. Trojanowicz et al. (2024) calculated the GQS by geophysical gravity inversion (GGI) technique over Colorado. Goyal et al. (2023b) investigated GQS term obtained from Flury and Rummel (2009) with difference in geoid and quasigeoid calculated using LSMSAC method aka KTH method.

The studies by the members of this JSG indicates further investigation is required to reach consensus on geoid/quasigeoid modelling techniques especially after incorporating all the requisite corrections and standardizations in the modelling and validation dataset. Further, cm-accurate and cm-precise geoid along with reaching some consensus in geoid/quasigeoid modelling techniques is also important from the viewpoint of IHRF realisations and unification of national vertical datums with IHRF.

Projects

The following three projects have been received by the members of this study group, the objectives of which aligns with the goals of JSG as can be observed by the project titles:

- Assessment of DEM error propagation in terrain corrections and its impact on geoid heights, conducted as part of the NAPGD2022 project. Canadian Geodetic Survey, Natural Resources Canada. Contributor: Dr. Ismael Foroughi
- Geoid Analysis using Rigorously Unique methods, for DEM & its Applications (GARUDA). Department of Science and Technology, Govt. of India. Contributor: Dr. Ropesh Goyal. 2024-2027
- Finding consensus between Stokes and Hotine for consistently-precise geoid determination using heterogeneous gravity data. Anusandhan National Research Foundation, Govt of India. Contributor: Dr. Ropesh Goyal. 2025-2028

Recognition to the members

- Ismael Foroughi served as President, Geodesy Section of the Canadian Geophysical Union 2023-2025. He was voted in as Vice-President of the Canadian Geophysical Union for the terms 2025-2027
- Bither Erol was elected as the Associate Analysis Centers (ASC) representative to the IHRF Directing Board in 2024. Sten Claessens has been recently elected to continue this position from June 2025
- 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

Interactions with the IAG Commissions and GGOS

The members of the groups are actively interacting, participating and contributing to the activities of IAG Commissions and GGOS. A few of the activities are as follows:

- IAG Workshop on Asia Pacific Gravity, Geoid, and Vertical Datums was organised during 6-8 November 2024 in Manila, Phillipines. The themes of the workshop were (i) Gravity data and digital elevation models (DEMs), (ii) Latest technologies in gravity measurement, (iii) Methods for gravimetric and hybrid geoid modelling, (iv) Quality control and GNSS/leveling campaigns for geoid models, (v) Coastal altimetry for geoid models and depth datums, (vi) Unifying Asia-Pacific height systems and depth datums, (vii) Gravity applications to studies of hazards, water resource management, and climatic changes, (viii) High quality and sustainable vertical reference frame (GGRF) to support United Nations Committee of Experts on Global Geospatial Information Management (UN-GGIM). The workshop was primarily an event of IAG Sub-commission 2.4e, which is chaired by Cheinway Hwang. Four other members of this JSG contributed to the Scientific committee of the workshop.

- Eleven members of this JSG also participates and contributes to JWG2.2.1: Comprehensive gravity data integration for the sub-cm geoid/quasi-geoid modelling, which is Chaired by Ismael Foroughi.
- International Height Reference Frame coordination centre and associate analysis centre. Eight members of this study group are participating in various activities of IHRF.
- Member of the group are also interacting the GGOS for exploring the joint organisation of online or hybrid workshops/schools pertaining to the mutual goals of the GGOS and JSG.

Refined plans for the period of 2025-2027

There are no refined plans for the period 2025-2027. However, with the continued activities of the members, the group shall:

- Organise sessions and splinter meetings in the two symposiums: Hotine-Marussi 2026 and Gravity, Geoid and Height System 2026, and IUGG General Assembly 2027.
- Jointly organise workshops or schools with GGOS, IGFS, IHRFCC and other JWG/JSGs of IAG commissions and sub-commissions.
- Explore sharing a common dataset, i.e., developed geoid/quasigeoid and ground truth data to run statistical tests for defining the terms “cm-accurate” and “cm-precise” along with the region-wise consistency for geoid/quasigeoid models.

Publications (Journals and Conferences)

Selected oral and poster presentations

Foroughi, I., Goli, M., Pagiatakis, S. D., Ferguson, S. (2023c). The power of airborne vector gravimetry for more accurate geoid models. In AGU Fall Meeting Abstracts (Vol. 2023, pp. G32A-02).

Foroughi, I., Goli, M., Pagiatakis, S., Ferguson, S. (2023d). Contribution of the horizontal components of airborne vector gravity measurements in geoid determination. In XXVIII General Assembly of the International Union of Geodesy and Geophysics (IUGG). GFZ German Research Centre for Geosciences.

Goyal, R., Claessens, S.J., Dikshit, O., Balasubramanian, N., (2023b). Investigating geoid-quasigeoid separation term with least squares modification of Stokes’s formula with additive corrections. In: 28th International Union of Geodesy and Geophysics General Assembly. July 11-20, 2023. Berlin, Germany.

Goyal, R., Sharma, B., Gaur, R., Gurjar, N., Dikshit, O., (2023c). An experimental setup for consistently precise Indian gravimetric geoid. In: American Geophysical Union Fall Meeting 2023. December 11-15, 2023, San Francisco, USA

Novák P, Šprlák M, Pitoňák M (2023) On Uncertainties Associated with Integral Transformations of Gravity Gradients. Poster presented at the AGU Fall Meeting, December 11-15, San Francisco, USA.

Pitoňák M, Šprlák M, Novák P (2023a) A Theoretical Study on Local Gravitational Field Modelling by the Spectral Combination of Satellite Higher-Order Radial Derivatives and a GGM. 28th IUGG General Assembly, July 11-20, Berlin, Germany.

Pitoňák M, Šprlák M, Novák P (2023b) Regional Gravitational Field Modelling by the Spectral Combination of Satellite Higher-Order Radial Derivatives of the Gravitational Potential and a Global Geopotential Model. European Geosciences Union General Assembly, April 23-28, Vienna, Austria.

Pitoňák M, Trnka P, Belinger J, Novák P, Šprlák M (2024a) A Novel MatLab-Based Software Library for the Calculation of Far-Zone Effects for Spherical Integral. Gravity, Geoid and Height Systems 2024, Joint IAG Commission 2, IGFS and GGOS Symposium, September 4-6, Thessaloniki, Greece.

Pitoňák M, Trnka P, Belinger J, Novák P, Šprlák M (2024b) FarZone4IT: A New Software for the Calculation of Far-Zone Effects for Spherical Integral. Poster presented at the European Geosciences Union General Assembly, April 14-19, Vienna, Austria.

Šprlák M, Pitoňák M, Trnka P, Belinger J, Novák P (2023) Far-Zone Effects for Integral Transformations: Theoretical and Numerical Aspects. 28th IUGG General Assembly, July 11-20, Berlin, Germany.

Selected peer-reviewed publications

Abbak, R. A., Goyal, R., Ustun, A., and Olgun, S. (2025). Combined effects of terrain corrections and deterministic modifiers on the Stokes-Helmert geoid over sophisticated topography. Acta Geodaetica et Geophysica, 60(1), 29–51.https://doi.org/10.1007/s40328-025-00460-7

Erol, B., Çevikalp, M. R., and Erol, S. (2023). Accuracy assessment of the SRTM2gravity high-resolution topographic gravity model in geoid computation. Survey Review, 55(393), 546–556. https://doi.org/10.1080/00396265.2023.2183332

Foroughi, I., Goli, M., Pagiatakis, S., Ferguson, S., and Novák, P. (2023a). Data requirements for the determination of a sub-centimetre geoid. Earth-Science Reviews, 239, 104326. https://doi.org/10.1016/j.earscirev.2023.104326

Foroughi, I., Goli, M., Pagiatakis, S., Ferguson, S., Vanicek, P., Santos, M., and Sheng, M. (2023b). The Uncertainties of the Topographical Density Variations in View of a Sub-Centimetre Geoid. In J. T. Freymueller and L. Sánchez (Eds.), X Hotine-Marussi Symposium on Mathematical Geodesy (Vol. 155, pp. 27–35). Springer International Publishing. https://doi.org/10.1007/1345_2023_189

Goyal, R., Claessens, S. J., Featherstone, W. E., and Dikshit, O. (2023a). Investigating the Congruence between Gravimetric Geoid Models over India. Journal of Surveying Engineering, 149(3), 04023005. https://doi.org/10.1061/JSUED2.SUENG-1382

Karaca, O., Erol, B., and Erol, S. (2024). Assessments of Gravity Data Gridding Using Various Interpolation Approaches for High-Resolution Geoid Computations. Geosciences, 14(3), 85. https://doi.org/10.3390/geosciences14030085

Marotta, G. S., Medeiros, D. F. D., Guimarães, G. D. N., and Erol, B. (2024). Investigation into the Effects of Different Parameters on Geoid Modeling Accuracy. Journal of Surveying Engineering, 150(2), 04024003. https://doi.org/10.1061/JSUED2.SUENG-1445

Pitoňák M, Šprlák M, Novák P (2023) Estimation of Height Anomalies from Gradients of the Gravitational Potential Using a Spectral Combination Method. In: International Association of Geodesy Symposia. Springer, Berlin, Heidelberg, https://doi.org/10.1007/1345_2023_194.

Pitoňák M, Trnka P, Belinger J, Šprlák M (2025) FarZone4IT: A MatLab-Based Software for the Calculation of Far-Zone Effects for Spherical Integral Transformations. Earth Science Informatics, 18(1), 54, https://doi.org/10.1007/s12145-024-01529-7.

Sansó, F., Barzaghi, R., and Reguzzoni, M. (2023). Molodensky's and Helmert's Theories: Two Equivalent Geodetic Approaches to the Determination of the Gravity Potential and the Earth Surface. In J. T. Freymueller and L. Sánchez (Eds.), X Hotine-Marussi Symposium on Mathematical Geodesy (Vol. 155, pp. 181–191). Springer International Publishing. https://doi.org/10.1007/1345_2023_212

Šprlák M, Pitoňák M (2024) Far-Zone Effects for Spherical Integral Transformations I: Formulas for the Radial Boundary Value Problem and Its Derivatives. Surveys in Geophysics, 45(3), pp. 977-1009, https://doi.org/10.1007/s10712-023-09818-4.

Trojanowicz, M., Owczarek-Wesołowska, M., and Wang, Y. M. (2024). Determination of the Geoid–Quasigeoid Separation Using GGI Method. Remote Sensing, 16(5), 816. https://doi.org/10.3390/rs16050816

Udama, Z. A., Claessens, S., Anjasmara, I. M., and Syafarianty, A. N. (2024). Analysis of different combinations of gravity data types in gravimetric geoid determination over Bali. Journal of Applied Geodesy, 18(3), 391–405. https://doi.org/10.1515/jag-2023-0042

Wang, Y. M., Veronneau, M., Huang, J., Ahlgren, K., Krcmaric, J., Li, X., and Avalos-Naranjo, D. (2023). Accurate computation of geoid-quasigeoid separation in mountainous region – A case study in Colorado with full extension to the experimental geoid region. Journal of Geodetic Science, 13(1), 20220128. https://doi.org/10.1515/jogs-2022-0128

Yang, M., Li, X., Lin, M., Deng, X.-L., Feng, W., Zhong, M., Shum, C. K., and Roman, D. R. (2023). On the harmonic correction in the gravity field determination. Journal of Geodesy, 97(11), 106. https://doi.org/10.1007/s00190-023-01794-2

JSG T.39: Gravitational field modelling and analysis for oblate and prolate planetary bodies

Chair: Michal Šprlák (Czech Republic)
Affiliation: Commission 2, ICGEM

Members:
Blažej Bucha (Slovakia)
Sten Claessens (Australia)
Mehdi Eshagh (Sweden)
Khosro Ghobadi-Far (USA)
Elmas Sinem Ince van der Wal (Germany)
Martina Idžanović (Norway)
Pavel Novák (Czech Republic)
Vegard Ophaug (Norway)
Georgios Panou (Greece)
Martin Pitoňák (Czech Republic)
Mahdiyeh Razeghi (Australia)
Natthachet Tangdamrongsub (Thailand)

Activities of the group

Members of JSG T.39 primarily focused on publishing in international journals on geodesy and geophysics (e.g., Journal of Geodesy or Surveys in Geophysics) and presenting their research findings at major international conferences (e.g., Joint IAG Commission 2, IGFS and GGOS Symposium; EGU General Assemblies; or AGU Fall Meetings). This effort has resulted in six peer-reviewed articles and 16 oral/poster presentations, suggesting active collaboration and a timely research area. The list of related research outputs is provided below and addresses all four objectives of JSG T.39.

Achievements and Results

Šprlák (2023, 2024) investigated orthogonality properties of spherical and spheroidal harmonic functions. Pitoňák et al. (2024a, 2024b, 2025b) developed the spectral combination for vertical and horizontal spheroidal boundary value problems. Belinger et al. (2024a, 2024b, 2024c) derived the spheroidal forward modelling in the spectral domain rigorously valid inside and outside the minimum Brillouin spheroid. Šprlák et al. (2023, 2024b) examined GRACE/GRACE-FO surface mass modelling by spherical and spheroidal harmonic functions. Koci and Panou (2024) estimated the defining parameters of a new biaxial reference ellipsoid of Somigliana-Pizzetti type for the Earth. Dohnalová et al. (2024) and Šprlák et al. (2024a) developed a software tool for the spheroidal gravitational field modelling in the spectral domain and investigated numerical aspects of selected mathematical functions.

Other research contributions relevant to the objectives of JSG T.39 considered the spherical approximation as a special case of the more complex spheroidal counterpart.

Sansò and Bucha (2023) investigated the change of boundary as a tool for global gravitational field modelling. Bucha (2024, 2025) developed a spectral gravity forward modelling of 3D variable densities using an arbitrary integration radius. Šprlák and Pitoňák (2024a, 2024b) and Pitoňák et al. (2025a) derived the far-zone effects for spherical integral transformations and provided a software package for their numerical calculation. Fatolazadeh et al. (2024, 2025) employed the spectral combination for the spatiotemporal downscaling of groundwater storage variation by GRACE and GRACE-FO observations.

Except for the scientific activities, members of JSG T.39 organised related sessions at international symposia. K. Ghobadi-Far co-organised the sessions "GRACE-FO and Beyond: Current Status, Analysis, and Method Advances and Future Missions" and "Satellite Gravimetry: Mission Concepts, Algorithms, and New Applications" at the AGU 2023 and 2024 Fall Meetings, respectively. P. Novák co-organised the session "Regional gravity field modelling and geophysical interpretation" at the Joint IAG Commission 2, IGFS and GGOS Symposium in 2024. G. Panou and M. Šprlák co-organised the sessions "Recent Developments in Geodetic Theory" and "Open Session in Geodesy with a Focus on Geodetic Theory" at the EGU General Assemblies 2024 and 2025, respectively.

Interactions with the IAG Commissions and GGOS

Members of JSG T.39 interact with researchers from JSG T.38, T.40, T.43, and ICGEM.

Publications

Selected oral and poster presentations

Bucha B (2024) Spectral Gravity Forward Modelling of Continuous 3D Variable Density Contrasts Using an Arbitrary Integration Radius. Gravity, Geoid and Height Systems 2024, Joint IAG Commission 2, IGFS and GGOS Symposium, September 4-6, Thessaloniki, Greece.

Belinger J, Dohnalová V, Pitoňák M, Novák P, Šprlák M (2024a) Global Gravitational Field Modelling for Spheroidal Planetary Bodies: Non-Singular Solutions. Poster presented at the European Geosciences Union General Assembly, April 27 - May 2, Vienna, Austria.

Belinger J, Dohnalová V, Pitoňák M, Novák P, Šprlák M (2024b) Global Gravitational Field Modelling for Spheroidal Planetary Bodies: Theory and Numerical Aspects. Poster presented at the Gravity, Geoid and Height Systems 2024, Joint IAG Commission 2, IGFS and GGOS Symposium, September 4-6, Thessaloniki, Greece.

Belinger J, Dohnalová V, Pitoňák M, Novák P, Šprlák M (2024c) Theory and Numerical Aspects of Global Gravitational Field Modelling for Spheroidal Planetary Bodies. Poster presented at the 13th Slovak Geophysical Conference, September 11-12, Bratislava, Slovakia.

Dohnalová V, Belinger J, Pitoňák M, Novák P, Šprlák M (2024) Global Gravitational Field Modelling for Flattened Planetary Bodies: Theory and Numerical Aspects. XXVIII Slovak-Polish-Czech Geodetic Days. May 30 - June 1, Trnava, Slovakia.

Fatolazadeh F, Eshagh M, Goita K (2024) Spectral Combination Approach for Spatiotemporal Downscaling of Groundwater Storage Variation Derived by GRACE and GRACE-FO Observations. 45th Canadian Symposium on Remote Sensing, June 10-13, Halifax, Canada.

Fatolazadeh F, Goita K, Wang S, Eshagh M (2025) Spectral Combination Approach for Spatiotemporal Downscaling of Groundwater Storage Variations Derived by GRACE and GRACE-FO Observations. Poster presented at the IEEE International Geoscience and Remote Sensing Symposium, August 3-8, Brisbane, Australia.

Koci J, Panou G (2024) A New Reference Equipotential Surface of the Earth. Poster presented at the Gravity, Geoid and Height Systems 2024, Joint IAG Commission 2, IGFS and GGOS Symposium, September 4-6, Thessaloniki, Greece.

Pitoňák M, Belinger J, Novák P, Šprlák M (2025b) Downward Continuation of the Gravitational Gradient Components to Gravitational Field Quantities by Spheroidal Spectral Combination Technique. European Geosciences Union General Assembly, April 27 - May 2, Vienna, Austria.

Pitoňák M, Šprlák M, Belinger J, Novák P (2024a) A Theoretical Study on the Spectral Combination of Vertical and Horizontal Spheroidal Boundary-Value Problems. Poster presented at the 13th Slovak Geophysical Conference, September 11-12, Bratislava, Slovakia.

Pitoňák M, Šprlák M, Belinger J, Novák P (2024b) Spectral Combination of Vertical and Horizontal Spheroidal Boundary-Value Problems: A Theoretical Study. Poster presented at the Gravity, Geoid and Height Systems 2024, Joint IAG Commission 2, IGFS and GGOS Symposium, September 4-6, Thessaloniki, Greece.

Šprlák M (2024) On Orthogonality Properties of Spherical and Spheroidal Harmonic Functions. Gravity, Geoid and Height Systems 2024, Joint IAG Commission 2, IGFS and GGOS Symposium, September 4-6, Thessaloniki, Greece.

Šprlák M, Ghobadi-Far K, Han S-C, Pitoňák M, Novák P (2023) GRACE/GRACE-FO Surface Mass Modelling by Spherical and Ellipsoidal Harmonics. Poster presented at the MAGIC Science and Applications Workshop, November 2-3, Assisi, Italy.

Šprlák M, Belinger J, Dohnalová V, Pitoňák M, Novák P (2024a) Global Gravitational Field Modelling for Flattened Bodies: Theoretical and Numerical Aspects. Poster presented at the AGU Fall Meeting, December 9-13, Washington DC, USA.

Šprlák M, Ghobadi-Far K, Han S-C, Pitoňák M, Novák P (2024b) GRACE/GRACE-FO Surface Mass Modelling by Spherical and Spheroidal Harmonics. Poster presented at the 13th Slovak Geophysical Conference, September 11-12, Bratislava, Slovakia.

Selected peer-reviewed publications

Bucha B (2025) Spectral Gravity Forward Modelling of 3D Variable Densities Using an Arbitrary Integration Radius with Application to Lunar Topographic Masses. Journal of Geodesy 99:31, https://doi.org/10.1007/s00190-025-01951-9.

Pitoňák M, Trnka P, Belinger J, Šprlák M (2025a) FarZone4IT: A MatLab-Based Software for the Calculation of Far-Zone Effects for Spherical Integral Transformations. Earth Science Informatics 18:54, https://doi.org/10.1007/s12145-024-01529-7.

Sansò F, Bucha B (2023) Change of Boundary: Towards a Mathematical Foundation of Global Gravity Models. Journal of Geodesy 97:63, https://doi.org/10.1007/s00190-023-01748-8.

Šprlák M (2023) Comments and Corrections to: "Ellipsoidal spectral properties of the Earth's gravitational potential and its first and second derivatives" by Bölling and Grafarend (2005) in J.Geod. 79(6-7):300-330. Journal of Geodesy 97:101, https://doi.org/10.1007/s00190-023-01799-x.

Šprlák M, Pitoňák M (2024a) Far-Zone Effects for Spherical Integral Transformations I: Formulas for the Radial Boundary Value Problem and Its Derivatives. Surveys in Geophysics, 45:977-1009, https://doi.org/10.1007/s10712-023-09818-4.

Šprlák M, Pitoňák M (2024b) Far-Zone Effects for Spherical Integral Transformations II: Formulas for Horizontal Boundary Value Problems and Their Derivatives. Surveys in Geophysics 45:1663-1713, https://doi.org/10.1007/s10712-024-09842-y.

JSG T.40: Modelling the gravity field of irregularly shaped celestial bodies

Chair: Zhi Yin (China)
Affiliations: Commissions 1,2, IGFS

Members:
Michal Šprlák (Czech Republic)
Biao Lu (Denmark)
Zuzana Minarechová (Slovakia)
Marek Macák (Slovakia)
Xiaole Deng (Germany)
Junsheng Liu (China)
Georgia Gavriilidou (Greece)
Yabo Duan (China)
Leyuan Wu (United Kingdom)
Blažej Bucha (Slovakia)
Qinglu Mu (China)
Dimitrios Tsoulis (Greece)
Kefei Zhang (China)
Nico Sneeuw(Germany)

Activities of the group

Members of JSG T.40 primarily focused on mutual cooperation and published their research findings in international journals on geodesy, geophysics and planetary sciences (e.g., Acta Astronautica, Reviews of Geophysics and Planetary Physics, Icarus or Journal of Geodesy). This effort has resulted in 12 peer-reviewed articles that suggests an active collaboration of the group members and actual research topic.

Achievements and Results

Bucha (2025) proposed a spectral forward modeling method that allows arbitrary integration radius for 3D variable density bodies, demonstrated through applications to lunar topographic masses.

Sansò and Bucha (2023) addressed the mathematical foundations of global gravity models from the perspective of boundary transformation.

Šprlák (2023) provided corrections and comments to classical formulations on the ellipsoidal spectral properties of the gravitational potential and its derivatives.

Bian et al. (2024, 2025) developed an optimized ensemble learning algorithm, integrating multi-source data to produce global oxide abundance and Mg# maps of the lunar surface.

Perkner and Šprlák (2025) estimated lunar crustal density using combined GRAIL and LRO gravity field models, contributing to the refinement of high-resolution lunar mass distributions.

Shao et al. (2025) investigated the key challenges and technical prospects of mineral separation and resource extraction from near-Earth asteroids.

Deng et al. (2025) proposed optimized formulas for the gravitational field of a vertical cylindrical prism using geometric relations and second-order 3D Taylor expansion to improve computational efficiency and accuracy.

Duan et al. (2025, ICARUS) proposed a novel inversion method for asteroid gravity fields based on geodesy Nets, which effectively addresses the issues of sparse data and complex boundary conditions.

Duan et al.(2024, Acta Astronautica) adopted CFD principles to model the gravity of ore-bearing asteroids, pioneering the application of fluid dynamics in gravity modeling for enhanced realism of mineral distribution.

Yin et al. (2024, Reviews of Geophysics and Planetary Physics) provided a comprehensive review of theoretical advances and challenges in gravitational field modeling in Earth sciences and planetary exploration.

Zhang et al. (2025, Space International) discussed the key role of remote sensing and geodetic surveying in asteroid exploration, particularly in object localization and 3D modeling.

Interactions with the IAG Commissions and GGOS

No significant interactions have been experienced with other JSGs and IAG entities.

Refined plans for the period of 2025-2027

Building upon the theoretical foundations established in previous studies, the group will focus on the practical implementation and validation of gravitational modeling methods in planetary science and deep-space exploration. Emphasis will be placed on applying the developed techniques—such as gravity inversion, forward modeling, and density estimation—to real mission data from small bodies (e.g., asteroids and the Moon). This includes integration with shape models, remote sensing observations, and gravity field measurements from current and upcoming planetary missions. Additionally, efforts will be directed toward the development of open-source tools and benchmarking datasets to facilitate broader scientific use and operational deployment.

Publications

Selected oral and poster presentations

Belinger J, Dohnalová V, Pitoňák M, Novák P, Šprlák M (2024) Global Gravitational Field Modelling for Spheroidal Planetary Bodies: Non-Singular Solutions. Poster presented at the European Geosciences Union General Assembly, April 27 - May 2, Vienna, Austria

Belinger J, Dohnalová V, Pitoňák M, Novák P, Šprlák M (2024) Global Gravitational Field Modelling for Spheroidal Planetary Bodies: Theory and Numerical Aspects. Gravity, Geoid and Height Systems 2024, Joint IAG Commission 2, IGFS and GGOS Symposium, September 4-6, Thessaloniki, Greece

Belinger J, Dohnalová V, Pitoňák M, Novák P, Šprlák M (2024) Theory and Numerical Aspects of Global Gravitational Field Modelling for Spheroidal Planetary Bodies. 13th Slovak Geophysical Conference, September 11-12, Bratislava, Slovakia

Dohnalová V, Belinger J, Pitoňák M, Novák P, Šprlák M (2024) Global Gravitational Field Modelling for Flattened Planetary Bodies: Theory and Numerical Aspects. XXVIII Slovak-Polish-Czech Geodetic Days. May 30 - June 1, Trnava, Slovakia

Macák M, Šprlák M, Minarechová Z (2024) Modelling Gravity Field of Irregularly Shaped Bodies by Numerical Methods. Poster presented at the European Geosciences Union General Assembly, April 14-19, Vienna, Austria

Perkner V, Šprlák M (2025) Lunar Crustal Density Estimate from the GRAIL and LOLA-Based Global Gravitational Field Models. Poster presented at the European Geosciences Union General Assembly, April 27 - May 2, Vienna, Austria

Perkner V, Šprlák M (2025) Lunar Crustal Density Estimate from the GRAIL and LRO-Based Global Gravitational Field Models. International Conference - Satellite Methods in Theory and Practice, February 4, Brno, Czech Republic (in Czech)

Pitoňák M, Belinger J, Novák P, Šprlák M (2025) Downward Continuation of the Gravitational Gradient Components to Gravitational Field Quantities by Spheroidal Spectral Combination Technique. European Geosciences Union General Assembly, April 27 - May 2, Vienna, Austria

Pitoňák M, Šprlák M, Belinger J, Novák P (2024) A Theoretical Study on the Spectral Combination of Vertical and Horizontal Spheroidal Boundary-Value Problems. 13th Slovak Geophysical Conference, September 11-12, Bratislava, Slovakia

Pitoňák M, Šprlák M, Belinger J, Novák P (2024) Spectral Combination of Vertical and Horizontal Spheroidal Boundary-Value Problems: A Theoretical Study. Gravity, Geoid and Height Systems 2024, Joint IAG Commission 2, IGFS and GGOS Symposium, September 4-6, Thessaloniki, Greece

Šprlák M (2024) On Orthogonality Properties of Spherical and Spheroidal Harmonic Functions. Gravity, Geoid and Height Systems 2024, Joint IAG Commission 2, IGFS and GGOS Symposium, September 4-6, Thessaloniki, Greece

Šprlák M, Belinger J, Dohnalová V, Pitoňák M, Novák P (2024) Global Gravitational Field Modelling for Flattened Bodies: Theoretical and Numerical Aspects. Poster presented at the AGU Fall Meeting, December 9-13, Washington DC, USA

Šprlák M, Ghobadi-Far K, Han S-C, Pitoňák M, Novák P (2023) GRACE/GRACE-FO Surface Mass Modelling by Spherical and Ellipsoidal Harmonics. MAGIC Science and Applications Workshop, November 2-3, Assisi, Italy

Šprlák M, Ghobadi-Far K, Han S-C, Pitoňák M, Novák P (2024) GRACE/GRACE-FO Surface Mass Modelling by Spherical and Spheroidal Harmonics. 13th Slovak Geophysical Conference, September 11-12, Bratislava, Slovakia

Šprlák M, Han S-C, Pitoňák M, Novák P (2023) Evaluation of External Spherical Harmonic Series Inside the Minimum Brillouin Sphere: Examples for the Lunar Gravitational Field. European Geosciences Union General Assembly, April 23-28, Vienna,

Austria

Šprlák M, Han S-C, Pitoňák M, Novák P (2023) GRAIL and LOLA Satellite Data Resolve the Long-Lasting Convergence/Divergence Problem for the Analytical Downward Continuation of the External Spherical Harmonic Expansions. International Seminar - Satellite Methods in Geodesy and Cadastre, February 1, Brno, Czech Republic

Selected peer-reviewed publications

Bian CF, Zhang KF, Wu YZ, et al. (2025) New maps of lunar surface oxide abundances and Mg# using an optimized ensemble learning algorithm, IEEE JSTAR, 18, pp. 9119-9134

Bian CF., Zhang KF, Wu YZ, et al. (2024) Mapping the spatial distributions of oxide abundances and Mg# on the lunar surface using multi-source data and a new ensemble learning algorithm, Planetary and Space Science,245

Bucha, B.(2025) Spectral gravity forward modelling of 3D variable densities using an arbitrary integration radius with application to lunar topographic masses. J Geod 99, 31

Deng, XL., Sneeuw, N., and Tsoulis, D. (2025). Optimized formulas of the gravitational field of a vertical cylindrical prism. Geo-Spatial Information Science, 1–14

Duan YB, Yin Z, Zhang KF, et al. (2024) Modeling the gravitational field of the ore-bearing asteroid by using the CFD-based method. Acta Astronautica,215,pp.664-673

Duan YB, Zhang KF, Yin Z, et al. (2025) A novel gravitational inversion method for small celestial bodies based on geodesyNets. ICARUS,433

Perkner V, Šprlák M (2025) Lunar Crustal Density Estimate from the GRAIL and LRO-Based Global Gravitational Field Models. In: Proceedings of the International Seminar - Satellite Methods in Theory and Practice, February 4, Brno, Czech Republic, pp. 85-91

Sansò, F., Bucha, B. (2023) Change of boundary: towards a mathematical foundation of global gravity models. J Geod 97, 63

Shao WK, Liu CM, Zhang KF, et al. (2025) Challenges and prospects for mineral separation and resource extraction from near-earth asteroids. Journal of Astronautics (accepted)

Šprlák M .(2023) Comments and Corrections to: "Ellipsoidal spectral properties of the Earth's gravitational potential and its first and second derivatives" by Bölling and Grafarend (2005) in J.Geod. 79(6-7):300-330. Journal of Geodesy, 97(11), 101

Yin Z, Zhang KF, Duan YB, et al. (2024) Theoretical research progress of gravitational field modeling in Earth science and deep-space exploration. Reviews of Geophysics and Planetary Physics,55(5): 501-512

Zhang KF, Liu ZL, Duan YB, et al. (2025) Application of surveying and remote sensing technology for asteroid exploration, Space International (accepted)

JSG T.41: Geodetic quality/integrity modelling, monitoring and design

Chair: Safoora Zaminpardaz (Australia)
Affiliations: Commissions 1,2,3,4

Members:
Jinling Wang (Australia)
Vinicius Francisco Rofatto (Brazil)
Krzysztof Nowel (Poland)
Cemal Özer Yiğit (Turkey)
Zhetao Zhang (China)
Ling Yang (China)
Carlos Fortuny Lombraña (Netherlands)
Christian Lisdat (Germany)

Activities of the group

This report outlines the activities of the ICCT Joint Study Group T.41 during the 2023–2025 period. The group's efforts were directed toward publishing in leading international journals in geodesy, such as the Journal of Geodesy and GPS Solutions, and sharing research outcomes at major international conferences such as EGU General Assembly. An online meeting was held to discuss challenges related to Geodetic Quality and Integrity and to promote collaboration through joint publications and international research initiatives.

Achievements and Results

Zhetao Zhang has been focused on geodetic quality under complex conditions, such as challenging environments, low-cost devices, multi-source data, etc. His work address several key topics: real-time kinematic multipath mitigation, outlier and cycle slip reliable processing, unmodeled error detection-compensation-control framework, biased ambiguity resolution, resilient PNT modes, see e.g. Haijun Yuan et al. (2023); Zhetao Zhang and Bofeng Li (2024); Zhetao Zhang, Yidi Yu et al. (2025); Zhetao Zhang, Li Wang et al. (2025); Zhetao Zhang, Xuezhen Li et al. (2023); Zhetao Zhang, Haijun Yuan et al. (2023); Zhetao Zhang, Jinwen Zeng et al. (2023); Jinwen Zeng, Zhetao Zhang et al. (2023). He attended 3 international conferences, including The 3rd IAG Commission 4 Symposium, IPIN 2024, and EGU General Assembly 2024. Since 2025, He has been serving as an Associate Editor for Advances in Space Research.

Over the past six months, Carlos Fortuny Lombraña has extended Teunissen's DIA-estimator framework (from "On the Optimality of DIA-Estimators: Theory and Applications," Journal of Geodesy, 98(5)) by incorporating a user-specified false-alarm probability (FAP) constraint directly into the acceptance partitioning $\mathcal{P}_0$. This innovation unifies penalty-driven integrity design with traditional false-alarm control. Whereas Teunissen's original method minimizes the "mean penalty" across misclosure partitions without bounding false alarms, and traditional GNSS integrity monitoring fixes $\mathcal{P}_0$ via a chi-squared threshold to meet a given FAP. This new formulation minimizes the mean penalty subject to the FAP constraint. He plans to attend the IAG Scientific Assembly 2025 in Rimini, Italy (1–5 September 2025) IAG, where he has submitted an abstract to a DIA session about an analysis of this new formulation which minimizes the mean penalty subject to the FAP constraint. Additionally, he is also preparing a Springer-published IAG Symposia Series proceedings paper. These investigations are expected to culminate in a forthcoming journal publication.

Vinicius Rofatto has focused on robust statistical modeling and quality assurance in geodetic and GNSS data processing, see e.g. Ismael Érique Koch et al. (2024); Ivandro Klein et al. (2025); Stefano Sampaio Suraci et al. (2025). He has developed innovative approaches for outlier detection, including confidence region-based decision rules and machine learning meta-classifiers tailored to GNSS networks, particularly under low redundancy conditions. his work bridges geodetic practice with statistical and metrological rigor, advancing the understanding of accuracy, precision, and trueness in positioning and deformation analysis. Additionally, he has contributed practical, data-driven models for GNSS variance–covariance estimation using widely accessible parameters, supporting improved network design and geometric integrity in relative positioning. He attended XIII Brazilian Colloquium of Geodetic Sciences - 2024 and been serving as Editorial Board member of the Journal of Surveying Engineering (ASCE) and the Associate Editor of the Revista Brasileira de Cartografia (RBC).

Krzysztof Nowel has participated in two publications related to the objectives of the group. In K Nowel and A Fischer (2025), a rigorous procedure for the quality control of geodetic deformation analysis considering its DIA-nature is proposed. The authors provided a necessary theory and numerical procedures for the truthful analysis of sensitivity and precision. K Nowel, A Fischer, and Cellmer S (2025) proposes a rigorous procedure for the quality control under regularized (ill-conditioned) mathematical models, based on a single-point positioning example. An implicit representation of the regularized mathematical model, free from the influence of regularization, was provided and the rigorous generalized likelihood ratio test was constructed.

Ling Yang's research has mainly focused on GNSS positioning, encompassing the development of advanced methodologies for the quality control of atmospheric corrections at the service-end, as well as the stochastical model refinement, outlier DIA (Detection, Identification, and Adaptation) and IM (Integrity Monitoring) methods at the user-end, see e.g. Ling Yang, Yunri Fu et al. (2023, 2024); Yangkang Yu, Ling Yang et al.(2023, 2024, 2025). Her research has successfully developed a cohesive suite of advanced statistical methods that significantly improve the capability to detect, identify, and mitigate the impact of outliers and residual systematic errors, particularly when multiple and diverse factors mixed together, in geodetic and GNSS data processing. These contributions provide powerful tools for enhancing the reliability, accuracy, and safety of positioning, navigation, and timing (PNT) systems in demanding applications like autonomous vehicles, precision agriculture, and aviation.

Safoora Zaminpardaz's research has focused on integrating parameter estimation with statistical testing to enhance model integrity and quality control, see e.g. Safoora Zaminpardaz and Peter JG Teunissen (2020, 2023, 2024, 2025); Teunissen, P.J.G. et al. (2024). She has investigated how this integration alters the statistical properties of estimators, leading to non-Gaussian behaviors that challenge traditional inference methods. To address these challenges, she has developed new frameworks for constructing confidence regions that accurately reflect the true distributions of estimators. She has highlighted the distinction between Minimal Detectable Bias (MDB) and Minimal Identifiable Bias (MIB), emphasizing that MDB reflects the ability to detect model errors, while MIB captures the ability to correctly identify their source. Safoora has designed algorithms for computing MDB and MIB and has analyzed their propagation through nonlinear estimators. In her most recent work, she has compared four variants of DIA estimators using the framework of minimum mean penalty testing. This analysis has revealed how different misclosure-space partitionings and penalty functions influence hypothesis identification accuracy and estimator safety.

Interactions with the IAG Commissions and GGOS

We have not encountered significant engagements with other JSGs and IAG entities.

Refined plans for the period of 2025-2027

The group intends to maintain a combination of virtual and face-to-face meetings to collectively tackle key research challenges. Ongoing collaboration is expected to intensify, with the goal of producing high-quality publications.

Publications

Selected oral and poster presentations

Zhang, Z. and B. Li. GNSS unmodeled error processing based on the resilient mathematical model compensation in high-precision GNSS positioning. In EGU General Assembly Conference Abstracts, page 4504, 2024.

Selected peer-reviewed publications

Bucher, I.É.K., I. Klein, L.G. Jr, V.F. Rofatto, M.T. Matsuoka, J.F.G. Monico, and M.R. Veronez. Metaheuristic-based stochastic models for GNSS relative positioning planning. GPS Solutions, 28(1):15, 2024.

Duan, I., V.F. Rofatto, and M.T. Matsuoka. Minimal influential error: a new tool to protect parameters from outliers. Measurement, 251:117288, 2025.

Klein, I., V.F. Rofatto, and M.T. Matsuoka. Minimal influential error: a new tool to protect parameters from outliers. Measurement, 251:117288, 2025.

Nowel, K. and A. Fischer. Quality control of geodetic deformation analysis considering its DIA-nature. Journal of Geodesy (under review), 2025.

Nowel, K., A. Fischer, and S. Cellmer. The statistical testing of regularized mathematical models in geodetic data processing. Journal of Geodesy, 99(14), 2025.

Sampaio Suraci, S., L.C. de Oliveira, I. Klein, R.R. Goldschmidt, and V.F. Rofatto. A meta-classification-based approach for outlier identification in GNSS networks. GPS

Solutions, 29(1):21, 2025.

Teunissen, P.J.G., S. Ciuban, C. Yin, B.G.v. Noort, S. Zaminpardaz, and C.C.J.M. Tiberius. The DIA-Estimator for Positional Integrity: Design and Computational Challenges. In: Freymueller, J.T., Sánchez, L. (eds) Together Again for Geodesy. IUGG 2023. International Association of Geodesy Symposia, vol 157. Springer, Cham., 2024 https://doi.org/10.1007/1345_2024_246.

Yang, L., Y. Fu, J. Zhu, Y. Shen, and C. Rizos. GNSS ionospheric integrity monitoring based on RBF-NN: constructing single-epoch snapshot GIVD and GIVE maps. Journal of Geodesy, 98(4):31, 2024.

Yang, L., Y. Fu, J. Zhu, Y. Shen, and C. Rizos. Overbounding residual zenith tropospheric delays to enhance GNSS integrity monitoring. GPS Solutions, 27(2):76, 2023.

Yu, Y., L. Yang, and Y. Shen. An extended w-test for outlier diagnostics in linear models. Journal of Geodesy, 98(6):58, 2024.

Yu, Y., L. Yang, and Y. Shen. A generalization of data snooping and data refining. Journal of Surveying Engineering (Accepted), 2025.

Yu, Y., L. Yang, Y. Shen, and A. El-Mowafy. Bayesian fault detection, identification, and adaptation for GNSS applications. IEEE Transactions on Aerospace and Electronic Systems, 2024.

Yu, Y., L. Yang, Y. Shen, and N. Sun. A DIA method based on maximum a posteriori estimate for multiple outliers. GPS Solutions, 27(4):199, 2023.

Yuan, H., X. He, Z. Zhang, H. Liu, Y. Li, and Z. Jiang. A real-time combined quality control method for GNSS precise positioning in harsh environments. Advances in Space Research, 71(1):900–911, 2023.

Zaminpardaz, S. and P.J.G. Teunissen. Conceptual and probabilistic comparison of DIA-estimators for bias-known hypothesis testing. Journal of Geodesy (Accepted), 2025.

Zaminpardaz, S. and P.J.G. Teunissen. Detection-only versus detection and identification of model misspecifications. Journal of Geodesy, 97(6):55, 2023.

Zaminpardaz, S. and P.J.G. Teunissen. Impact of outlier monitoring on confidence regions: GNSS positioning examples. In Proceedings of the 37th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2024), pages 1731–1740, 2024.

Zaminpardaz, S. and P.J.G. Teunissen. MDBs versus MIBs in case of multiple hypotheses: A study in context of deformation analysis. In X Hotine-Marussi Symposium on Mathematical Geodesy, page 73, 2023.

Zaminpardaz, S., P.J.G. Teunissen. GNSS Detection and Estimation Integrity. In: Sideris, M.G. (eds) Encyclopedia of Geodesy. Encyclopedia of Earth Sciences Series. Springer, Cham. https://doi.org/10.1007/978-3-319-02370-0_170-1,2023.

Zeng, J., Z. Zhang, X. He, H. Yuan, Y. Li, and M. Song. Real-time GNSS multiple cycle slip detection and repair based on a controllable geometry-based method in relative positioning. Measurement, 216:112940, 2023.

Zhang, Z., H. Yuan, X. He, and J. Zeng. Cycle slip detection and repair based on the unmodeled-error-constrained geometry-free combining geometry-based models for a single-frequency receiver. Measurement, 217:113090, 2023.

Zhang, Z., J. Zeng, B. Li, and X. He. Principles, methods and applications of cycle slip detection and repair under complex observation conditions. Journal of Geodesy, 97(5):50, 2023.

Zhang, Z., L. Wang, and X. Li. Characterization and modeling of GNSS site-specific unmodeled errors under reflection and diffraction using a data-driven approach. Satellite Navigation, 6(1):8, 2025.

Zhang, Z., X. Li, H. Yuan, and Y. Luo. An enhanced outlier processing approach based on the resilient mathematical model compensation in GNSS precise positioning and navigation. Measurement Science and Technology, 35(1):015007, 2023.

Zhang, Z., Y. Yu, X. Li, and X. He. Reliable GNSS positioning and navigation with simultaneous multipath and NLOS mitigation by using camera and C/N0 at deep canyons. Measurement Science and Technology, 36(4):046308, 2025.

JSG T.42: Theoretical developments and applications of combined methods for a better understanding of the Earth's lithospheric formation, structure, and dynamics

Chair: Robert Tenzer (China-Hong Kong)
Affiliations: Commissions 2,3

Members:
Mohammad Bagherbandi (Sweden)
Mirko Reguzzoni (Italy)
Aleksej Baranov (Russia)
Franck Ghomsi (Cameroon)
Wenjin Chen (China)
Mehdi Eshagh (Sweden, Czech Republic)
Jianli Chen (China-Hong Kong)
Luan Thanh Pham (Vietnam)
Rebekka Steffen (Sweden)
Jose Manuel Ferrandiz Leal (Spain)
Bernhard Steinberger (Germany)

Activities of the group

This report outlines the activities of the ICCT Joint Study Group T.42 during the 2023–2025 period. The group's efforts were directed toward publishing in leading international journals and sharing research outcomes at major international conferences.

Achievements and Results

Eshagh et al. (2024) provided a comprehensive overview of theoretical definitions describing relationships between the spherical harmonic coefficients and different satellite gravimetry observables such as orbital perturbations in terms of satellite positions, velocities, and accelerations; satellite-to-satellite range rates; and gravitational gradients. They presented and discussed products and applications of the Earth's static global gravitational models in the context of determination of the gravimetric geoid and physical heights, gravimetric and isostatic crustal thickness, bathymetric depths, glacier bedrock relief, sediment thickness, geostrophic and eddy currents, Earth's inertia tensor and dipole, precession and nutation parameters of the Earth's rotation, and prediction of the satellite orbital geometry. Furthermore, they presented applications and advances of the Earth's time-variable gravitational models for monitoring large earthquakes, hydrological mass transport, Earth's rotation parameters, and vertical crustal motions (due to the glacial isostatic adjustment and other phenomena) and discussed future trends and prospects in the satellite gravimetry are discussed.

Baranov et al. (2025) investigated the evolution of horizontal stress field after implementing a supercontinent into spherical mantle model with phase transitions, the temperature- and pressure-dependent rheology, while assuming that the mantle is heated from the base and from within. They demonstrated that before implementation of the supercontinent, the overlithostatic horizontal stresses in the areas of mantle upwellings/downwellings are about ±25 MPa and more, whereas for the rest upper mantle horizontal stresses are in the range of ±15 MPa. The supercontinent covered one-third of the Earth's surface and it is modeled as an undeformable, highly viscous immobile lid with respect to the ambient mantle and it is abruptly imposed on well-developed mantle convection. The area of supercontinent is limited by a spherical angle ($\theta \leq 66.4°$). According to their results, after implementation, the mantle flow is rearranged and a group of upwelling mantle flows is formed under the supercontinent and their hot heads increase in size due to the heat-insulating effect of the supercontinent, while quasi-linear subduction zones increase in the oceanic regions. As a result, the average temperature of the area under the supercontinent rises over time and becomes higher than the average temperature of the suboceanic area, where cold descending mantle flows intensify. At the depth covering the interval from 300 to 400 km under the supercontinent the temperature rises on average by 60 K. Formed under the supercontinent, upwelling mantle flows dramatically change the stress pattern in the supercontinental area producing tensional stresses in the supercontinent and overlithostatic compressive horizontal stresses in the subcontinent mantle. Tensile overlithostatic horizontal stresses inside the supercontinent change from 25 to 50 MPa in different continental areas, whereas beneath the supercontinent the overlithostatic compressive horizontal stresses in the subcontinent mantle are about 20-60 MPa. Only for the model with weak zone around the supercontinent stresses can reach 100 MPa.

Ma et al. (2024) applied the Spherical Slepian functions (SSFs) to determine mean sea level (MSL) variations in the South China Sea. Their sensitivity simulation in terms of trend, annual amplitude, and phase revealed that the SSF solution with a 1' coastal buffer zone provides a better land-to-ocean leakage correction than traditionally used Spherical Harmonics (SH). They also found that an additional smoothing procedure for SSF with low concentrating energy could significantly reduce the high-frequency noise in GRACE (e.g., the north–south strips). Furthermore, they compared the spatiotemporal characteristics of the true MSL among GRACE SH and Mascon solutions, model-predicted ocean bottom pressure, and steric-corrected altimetric data (i.e., satellite-altimetric sea level minus steric effect). Their results revealed that despite the SSF-inverted regional MSL solution being generally similar to other results, this technique notably recovered the realistic magnitude of detailed features. The apparent MSL signal was, for instance, precisely recovered in the central part of the Gulf of Thailand and the Sunda Shelf by the SSF, while the SH significantly underestimated it due to smoothing. In addition to the seasonality, the interannual signal decomposed from the SSF-inverted residual MSL (by removing the trend and periodic signals) was the strongest and well cross-correlated with the Southern Oscillation Index. With more detailed spatial patterns revealed by MSL from GRACE SSF, our findings demonstrate that SSF is more suitable for regional-scale studies.

Baranov et al. (2024) used seismic surveys (853 stations and 79 seismic profiles) to compile a new continental Moho model of the African continent (see Fig. 1) of which 90% is formed by the Precambrian crust. Their result reveals considerable Moho depth variations, with values ranging from 14 to 20 km for the Afar Triple Junction and

Turkana Lake to 46 km beneath the Rif Mountains, parts of the Ethiopian Plateaus, and the Namaqua-Natal Belt. They found a localized Moho deepening (∼44 km) beneath the western and eastern blocks of the Congo Craton, the central part of Victoria Lake, the Rehoboth Province, the eastern part of the Kaapvaal Craton, and the Irumide Belt. They detected a shallow Moho depth beneath wide areas in North, Central, and East Africa, particularly along the North Africa coast (24–30 km), the Mauritanian Belt (26–30 km), the West and Central African Rift System (30–32 km), the Benue Trough (24–28 km), and beneath the Rwenzori Mountains (26–30 km) and the southern part of Somali Plate (22–26 km). Moho relief at many locations is characterized by significant changes across different tectonic provinces; from the Afar Triple Junction, Turkana Depression, and the Somali Plate to the Main Ethiopian Rift, between the Rwenzori region, from the Gabon-Cameroon Shield to the Benue Trough, and from the western border of the West African Craton to the Mauritanian Belt. According to their estimates, an average Moho depth beneath the African continent is 36.1 km.

Chen et al. (2024) developed open-source software for a gravimetric forward modelling (GFM) that incorporates a graphical user interface. This software allows data preparation, manipulation and result interpretation both spatially and spectrally. For spatial domain modelling, it uses prism and tesseroid elements, whereas in the spectral domain, it extends Parker's formulas within specified boundaries. Performance comparisons show that Parker's method delivers computation speed superior to that of the prism, tesseroid and terrain gravity forward (TGF) software, with variances ranging within ±12 mGal and ±0.3 E across different geological scenarios. The diagram of software architecture is shown in Fig. 2, and the software interface in Fig. 3.

Tenzer at al. (2025) conceptualized the definition of the radial integral of the geopotential, and derived functional relationships between this quantity and other parameters of the Earth's gravity field via Hotine and Stokes integrals (see Figs. 4 and 5). In numerical studies, they demonstrated that the application of radial integral operator smooths a spatial pattern of the disturbing potential. This finding is explained by the fact that more detailed features in the disturbing potential (mainly attributed to a gravitational signature of lithospheric density structure and geometry) are filtered out proportionally with increasing degree of spherical harmonics in this functional. In the global geoidal geometry (and the disturbing potential), on the other hand, the gravitational signature of lithosphere is still clearly manifested - most notably across large orogens - even after applying either spectral decompensation or filtering.

The group of Politecnico di Milano, in cooperation with INGV, GReD and Universities of Ferrara and Siena, worked on the modelling of the crustal structure in Central Italy, particularly under the Borexino detector of the Gran Sasso National Laboratory for supporting geoneutrino investigations. The 3D geophysical crustal model is computed by inverting the gravity field data and exploiting some a priori information derived from a combination of geological maps, stratigraphic information and seismic data. In particular, 53 wells from the ViDEPI project (Assomineraria, 2025) located in the area under study were considered, as well as 38 two-dimensional cross-sections. The Moho depth map by Spada et al. (2013) was incorporated into the a priori model as a grid with a 2 km spacing. Additional 154 punctual measurements of the Moho discontinuity coming from several seismic and teleseismic receiver function analyses

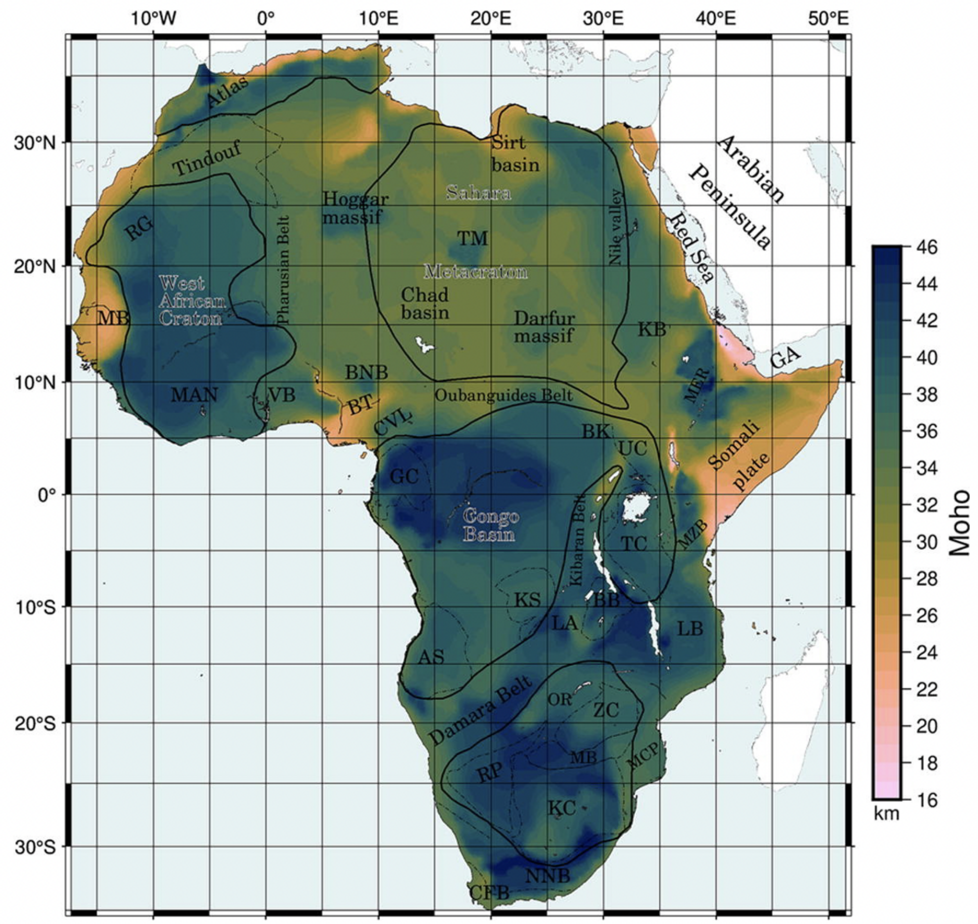

Fig. 1. The AFROMOHO African Moho model. Used abbreviation (alphabetical): AS = Angolan Shield; BB = Bangweulu Block; BK = Bomu-Kibalian Shield; BNB = Benin-Nigerian block; BT = Benue Trough; CFB = Cape Fold Belt; CVL = Cameroon Volcanic Line; GA = Gulf of Aden; GC = Gabon-Cameroon Shield; IB = Irumide Belt; KB = Khartoum Basin; KC = Kaapvaal Craton; KS = Kasai Shield; LA = Lufilian Arc; LB = Lurio Block; MAN = Man-Leo Shield; MB- Mauritanian Belt; MB = Magondi Belt; MCP = Mozambique Coastal Plane; MZB = Mozambique Belt; MER = Main Ethiopian Rift; MR = Malawi Rift; NNB = Namaqua-Natal Belt; OR = Okavango Rift; RG = Reguibat Shield; RP = Rehoboth province; TC = Tanzania Craton; TM = Tibesti Massif; UC = Ugandan Craton; VB = Volta Basin; ZC = Zimbabwe Craton.

were used to better constrain the Moho depth. The gravity data set was obtaining by integrating the database used for the national geoid computation with a global gravity model. The gravity inversion was performed by the Bayesian approach (Reguzzoni et al., 2019), considering the main fault of the area under study and dividing the 3D

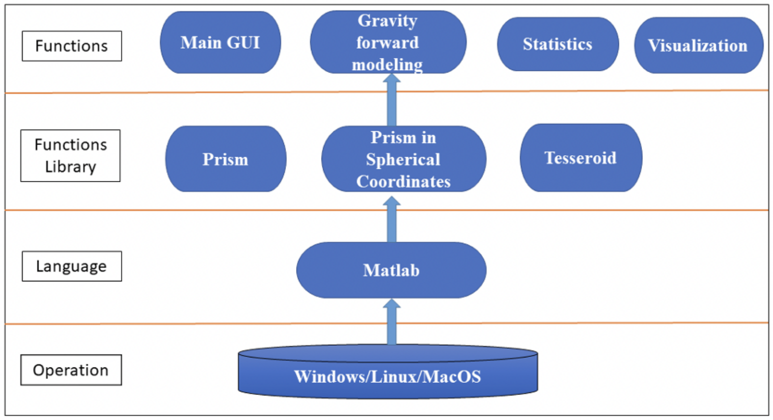

Fig. 2. The software architecture.

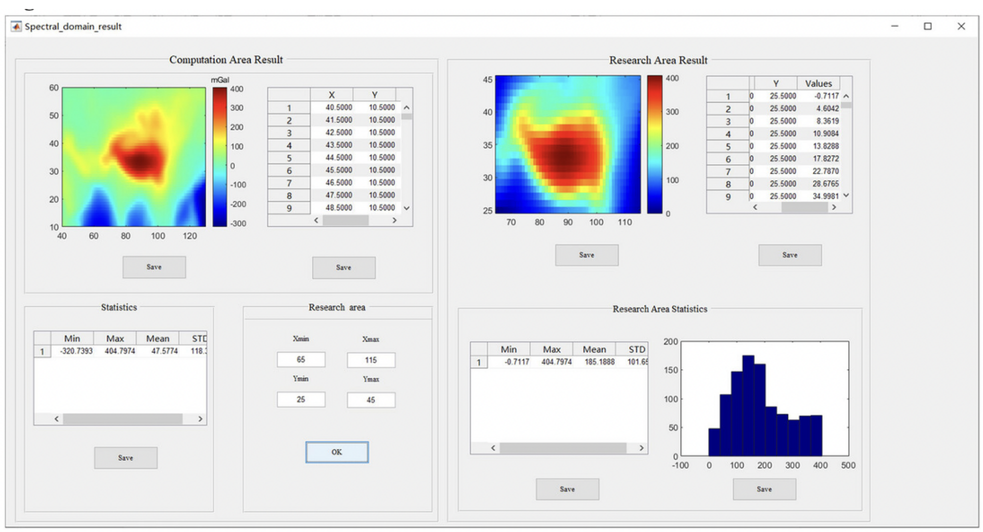

Fig. 3. The result interface of the gravimetric forward modelling (GFM) software in spectral domain.

model into the Adriatic and Tyrrhenian plates. The posterior distribution was maximized by means of stochastic optimization through Monte Carlo methods, leading to satisfactory results for the purpose of geonetrino investigations.

Bagherbandi et al. (2022) studied the Earth's mass redistribution due to deglaciation and recent ice sheet melting that causes changes in the Earth's gravity field and vertical land motion in Greenland. The changes are because of ongoing mass redistribution and related elastic (on a short time scale) and viscoelastic (on time scales of a few thousands of years) responses. These signatures can be used to determine

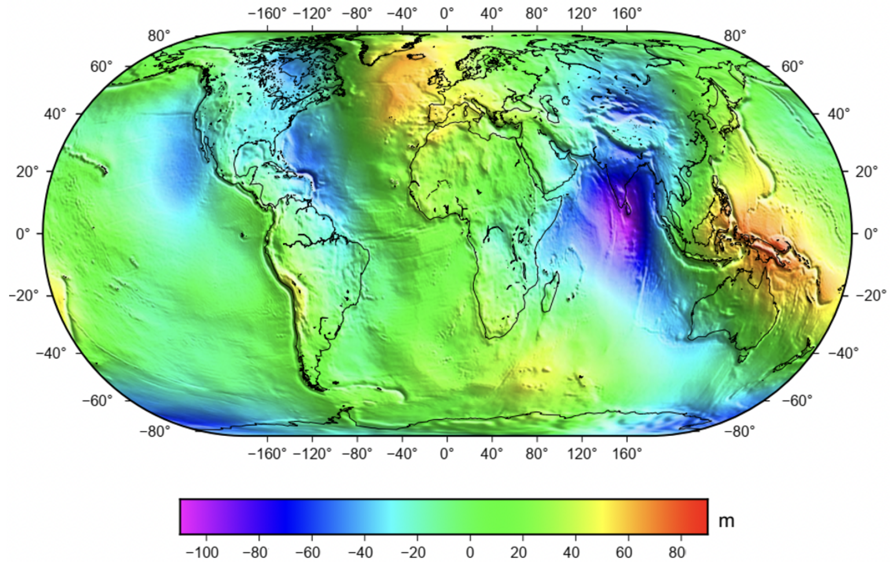

Fig. 4. Global geoidal undulations (m) computed on the 1 arc-deg equiangular grid using the EIGEN-6C4 coefficients (n = 2, 3, ..., 2160).

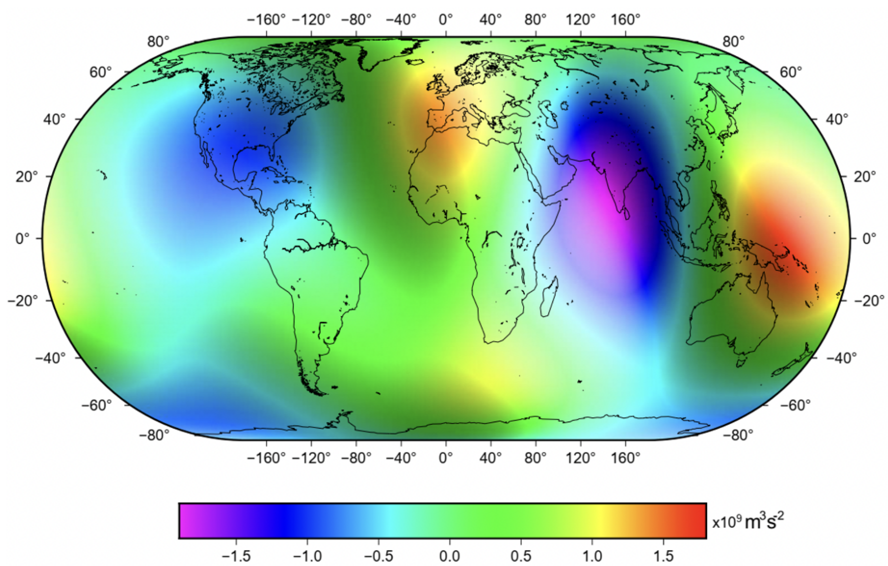

Fig. 5. Global map of the indefinite radial integral of the disturbing potential (m^3 s^{-2}) computed on the 1 arc-deg equiangular grid using the EIGEN-6C4 coefficients (n = 2, 3, ..., 2160).

the mantle viscosity (see Tab. 1). They infer the mantle viscosity associated with the glacial isostatic adjustment (GIA) and long-wavelength geoid beneath the Greenland lithosphere. The viscosity was determined based on a spatio-spectral analysis of the Earth's gravity field and the land uplift rate in order to find the GIA-related gravity field. They used different land uplift data, i.e. the vertical land motions obtained by the Greenland Global Positioning System (GPS) Network (GNET), GRACE and Glacial Isostatic Adjustment (GIA) data, and also combined them using the Kalman filtering technique (see Figs. 6 and 7). Using different land uplift rates, one can obtain different GIA-related gravity fields. According to their results, the mantle viscosities of 1.9×10^{22} Pa s and 7.8×10^{21} Pa s for a depth of 200 to 650 km were found based on using ICE-6G (VM5a) model and the combined land uplift model, respectively, and the GIA-related gravity potential signal.

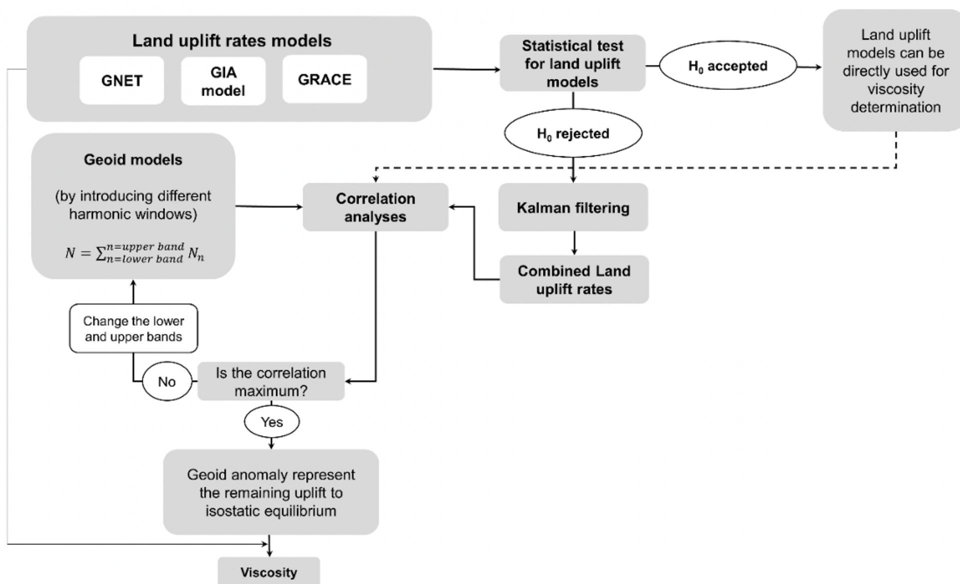

Fig. 6. Flowchart of viscosity determination using geoid anomaly and different land uplift rates.

Gholamrezaee et al. (2023) studied the sea surface height determination using GNSS Reflectometry (GNSS-R) approach and proposed a method to determine the tidal frequencies more precisely. Monitoring essential climate variables (ECVs) using remote sensing observations provides the opportunity to study their regional and global impacts. Coastal Global Navigation Satellite System (GNSS) stations enable water level measurement using the GNSS-R technique. Using GNSS-R, the vertical distance between the antenna and the reflective surface (e.g., water surface) can be obtained in the vertical (height) reference frame. They used the signal-to-noise ratio (SNR) data from four selected stations over three months for this purpose. The obtained

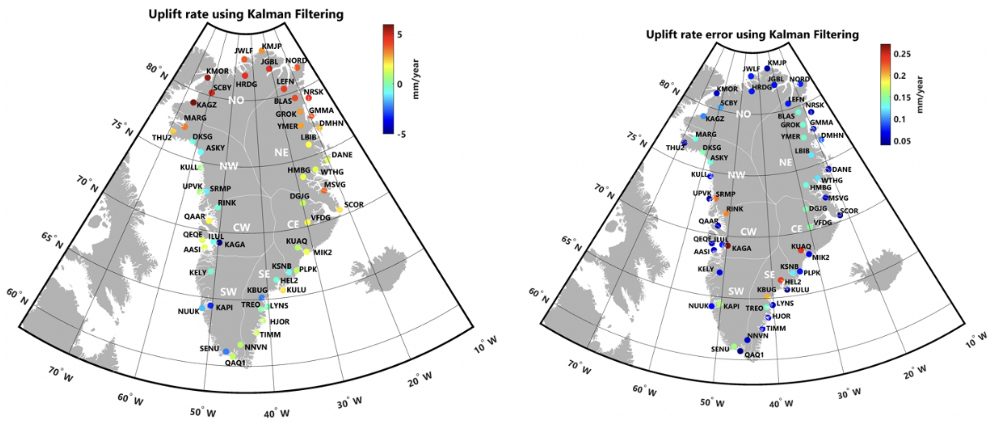

Fig. 7. Estimated uplift rates at the GNET sites using GRACE, GPS data and GIA model (Caron et al., 2018) and employing the Kalman filtering approach. Unit: mm/year.

Table 1. Mantle viscosity obtained using different scenarios.

Scenarios	**Data**	**Harmonic window**	**Correlation coefficient**	**Viscosity** (Unit: Pa s)	**Uncertainty** (Unit: Pa s)
Scenario 1	EGM2008 ICE-6G (VM5a)	$10 \leq n \leq 39$	0.65	1.9×10^{22}	—
Scenario 2	EGM2008 Caron et al. 2018	$11 \leq n \leq 26$	0.68	9.2×10^{21}	1.2×10^{17}
Scenario 3	EGM2008 GNET uplift rate	$18 \leq n \leq 25$	0.40	1.3×10^{21}	2.6×10^{16}
Scenario 4	EGM2008 GRACE GIA uplift rate	$11 \leq n \leq 26$	0.68	5.1×10^{21}	1.2×10^{17}
Scenario 5	EGM2008 Combined GIA uplift rate	$11 \leq n \leq 26$	0.68	7.8×10^{21}	1.4×10^{17}

sea surface heights (SSH) were assessed using the nearest tide gauge observations. They investigated daily and hourly GNSS observations and used single frequencies of GPS (L1, L2 and L5), GLONASS (L1 and L2), Galileo (L1, L5, L6, L7 and L8), and BeiDou (L2 and L7) to estimate the SSH. They investigated which GNSS signals are accurate for SSH estimation (Fig. 8). In the following, using the time series derived from the best GNSS signal and tide gauge readings, the tidal frequencies are extracted and compared using the Least Square Harmonic Estimation (LS-HE) approach. The findings demonstrate that 145 significant tidal frequencies can be extracted using the GNSS-R time series. The existence of an acceptable correlation between the tidal frequencies of the GNSS-R and the tide gauge time series indicates the usefulness of the GNSS-R time series for tide studies. From the results, they concluded that the GNSS-R technique can be applied in coastal locations alongside tide gauge measurements for various purposes.

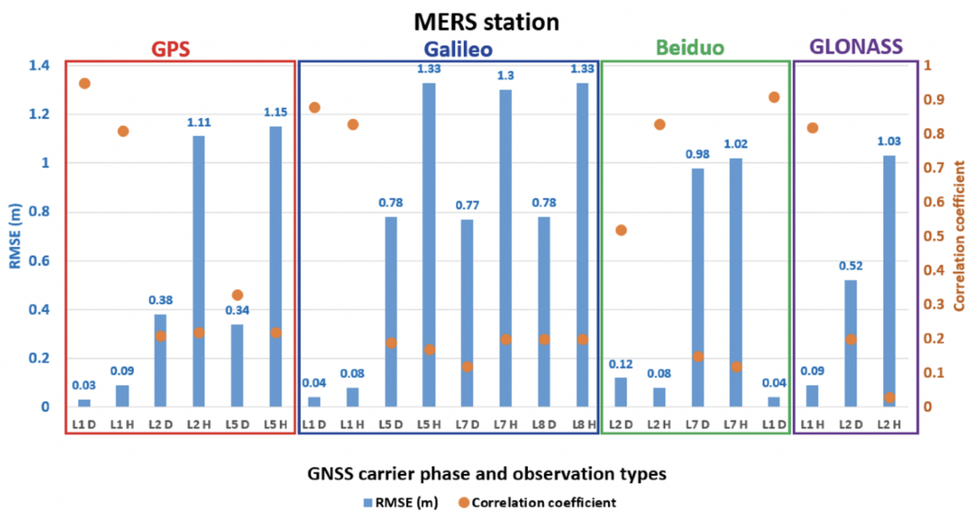

Fig. 8. Comparison of different GNSS signals and observation types using GNSS-IR and tide gauge data at MERS station (D = Daily and H = Hourly).

Dashtbazi et al. (2023) compiled a high resolution global Moho model from combining gravimetric and seismic data by using spectral combination methods. Such model is required in various geophysical studies. However, the available models' resolutions could be improved for this purpose. Large parts of the world still need to be sufficiently covered by seismic data, existing global Moho models do not fit the present-day requirements for accuracy and resolution. The isostatic models can relatively reproduce a Moho geometry in regions where the crustal structure is in an isostatic equilibrium, but large segments of the tectonic plates are not isostatically compensated, especially along active convergent and divergent tectonic margins. Isostatic models require a relatively good knowledge of the crustal density to correct observed gravity data. To overcome lack of seismic data and non-uniqueness of gravity inversion, seismic and gravity data should be combined to estimate Moho geometry more accurately. To address this issue, they investigated the performance of two techniques for combining long- and short-wavelength Moho geometry from seismic and gravity data (Fig. 9). Their results demonstrated that both Butterworth and spectral combination techniques can be used to model the Moho geometry. The results show the RMS of Moho depth differences between our model and the reference models are between 1.7 and 4.7 km for the Butterworth filter while between 0.4 and 4.1 km for the spectral combination.

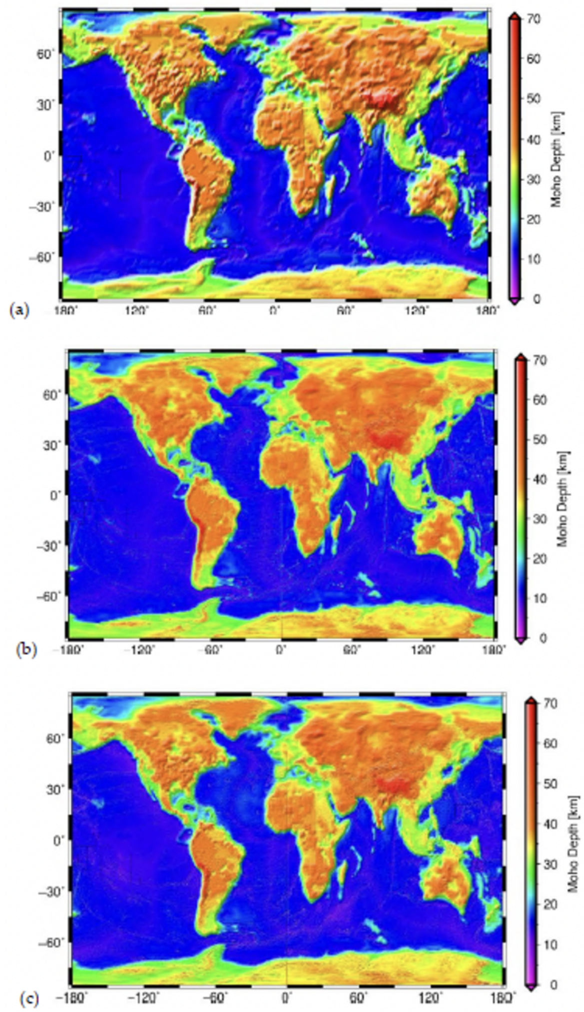

Fig. 9. Global Moho depth models: a) the CRUST1.0 model (with the resolution of 1'× 1'), b) the HRCM model obtained by applying the Butterworth filter (with the resolution of 5'×5'), and c) the HRCM model obtained by using the spectral combination method (with the resolution of 5'×5').

Bagherbandi et al. (2023) studied time transfer and significance of vertical land motion in relativistic geodesy applications. Determination of the Earth's gravity field and geopotential value is one of the fundamental topics in physical geodesy. Traditional terrestrial gravity and precise leveling measurements can be used to determine the geopotential values at a local or regional scale. However, recent developments in optical atomic clocks have not only rapidly improved fundamental science but also contributed to applied research. The latest generation of optical clocks is approaching the accuracy level of 10^{-18} when facilitating atomic clock networks. These systems allow examining fundamental theories and many research applications, such as atomic clocks applications in relativistic geodesy, to precisely determine the Earth's gravity field parameters (e.g., geopotential values). According to the theory of relativistic geodesy, the frequency difference measured by an optical clock network is related to the gravity potential anomaly, provided that the effects of disturbing signals (i.e., tidal and non-tidal contributions) are filtered out. The relativistic geodesy principle could be used for a practical realization of global geodetic infrastructure, most importantly, a vertical datum unification or realization of height systems. In their study, authors reviewed the background of relativistic (clock-based) geodesy and studied the variations of optical atomic clock measurements (e.g., due to hydrology loading and land motion). They studied the performance and recent developments of optical atomic clocks and the most fundamental theoretical definitions in relativistic geodesy. In addition, they reviewed different methods for high-performance clock networks, i.e., different methods for transferring frequency using optical atomic clocks. They also studied the variations of optical atomic clock measurements due to tidal and non-tidal contributions. In addition, they investigated the vertical land motions due to hydrology loading, other geophysical phenomena and their impact on the optical atomic clock measurements. Finally, they proposed a practical approach (using precise leveling) to validate the performance of relativistic geodesy.

Bagherbandi and Sjöberg (2025) developed a method to study the GIA related surface gravity versus height changes in Fennoscandia (Tab. 2). Vertical land motion and the redistribution of masses within and on the surface of the Earth affect the Earth's gravity field. Hence, studying the ratio between temporal changes of the surface gravity and height is important in geoscience, e.g., for reduction of gravity observations, assessing satellite gravimetry missions, and tuning vertical land motion models. Sjöberg and Bagherbandi (2020) estimated a combined ratio in Fennoscandia based on relative gravity observations along the 63 degree gravity line running from Vågstranda in Norway to Joensuu in Finland, 688 absolute gravity observations observed at 59 stations over Fennoscandia, monthly gravity data derived from the GRACE satellite mission between January 2003 and August 2016, as well as a land uplift model. The weighted least squares solution of all these data was $= -0.166 \pm 0.011$ μGal/mm, which corresponds to an upper mantel density of about 3402 ± 95 kg/m^3. The present note includes additional GRACE data to June 2017 and GRACE Follow-on data from June 2018 to November 2023. The resulting weighted least-squares solution for all data is $= -0.160 \pm 0.011$ μGal/mm, yielding an upper mantel density of about 3546 ± 71 kg/m^3. The outcomes show the importance of satellite gravimetry data in Glacial Isostatic Adjustment (GIA) modeling and other parameters such as land uplift rate (Fig. 10). Utilizing a longer time span of GRACE and GRACE Follow-on data allows us to capture fine variations and trends in the gravity-to-height ratio with better precision. This will be useful for constraining and adjusting GIA models and refining gravity observations. They modelled the gravity change (in μGal/yr) using the monthly solution of GRACE (and GRACE-FO) mission by

$$\dot{g}(P) = (-0.3086 + 0.1119 \frac{\rho_P^{mantle}}{2670}) \dot{h}(P) \tag{1}$$

where −0.3086 is the free-air gravity change, 0.1119 is the Bouguer plate contribution in μGal/mm (cf. Heiskanen and Moritz 1967, p. 131), 2670 is the crustal density in kg/m^3, ρ_m is the upper mantle density and $\dot{h}(P)$ is the land uplift rate at point P which is determined by monthly solution of the GRACE and GRACE-FO missions.

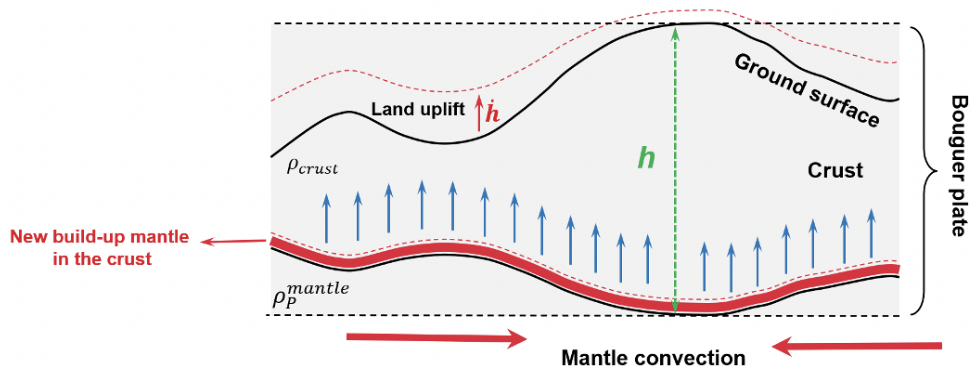

Fig. 10. GIA effect on the Earth's ground and the crust-mantle boundary (the image is not to scale).

Table 2. A comparison of the estimated ratio obtained by different studies.
(Notes: "1" weighted mean of $\dot{g}/\dot{h}$ obtained using all $\dot{g}/\dot{h}$ in the absolute gravity stations in Fennoscandia. "2" obtained by linear regression using all $\dot{g}/\dot{h}$ in the absolute gravity stations in Fennoscandia (see Fig. 11). "3" combined solution by the weighted mean method using Sjöberg 1989, Olsson et al. 2019 solutions, and the estimated value in "1".)

Source	$\dot{g}/\dot{h}$ (μGal/mm)	$\dot{g}/\dot{h}$ (μGal/mm)	**Intercept (in linear regression)**
Sjöberg 1989 and 1990	-0.162 ± 0.038		—
Ekman and Mäkinen 1996	-0.204 ± 0.058		—
Olsson et al. 2019	-0.163 ± 0.016		0.030
Sjöberg and Bagherbandi 2020 (GRACE only data)	Weighted[1] Linear regression[2] Combined[3]	-0.172 ± 0.018 -0.210 ± 0.004 -0.166 ± 0.011	— 0.288 ± 0.021 —
This study (using GRACE and GRACE-FO data)	Weighted[1] Linear regression[2] Combined[3]	-0.156 ± 0.016 -0.187 ± 0.003 -0.160 ± 0.011	— 0.240 ± 0.019 —

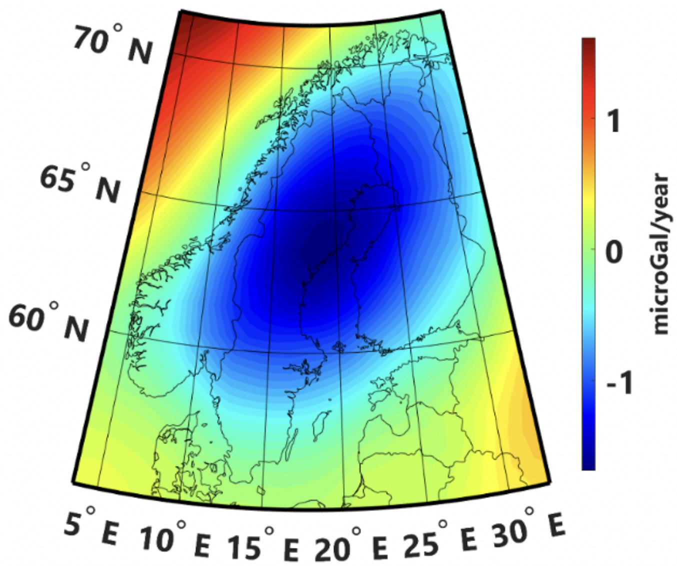

Fig. 11. Surface gravity change ($\dot{g}$) obtained using CSR GRACE and GRACE-FO RL06 data (from January 2003 to November 2023) in Fennoscandia.

Steinberger and Cui (2025) modelled geoid and dynamic topography from tomography-based thermo-chemical density anomalies in the lithosphere and convecting mantle beneath, and provided constraints on the depth distribution of lithosphere density anomalies. One of the surface expressions of mantle convection is dynamic topography, as the the surface is uplifted above upwellings and pulled down above downwellings. However, it is challenging to extract the topography signal from the convecting mantle, because of large isostatic topography contributions from within the crust and subcrustal lithosphere. Technically, the latter can be included as part of dynamic topography but that needs to be clearly specified to avoid confusion. They used two recent crustal models to subtract crustal isostasy, and show that the remaining (residual) topography signal as well as the geoid can be matched well by a model where density anomalies and temperatures in the subcrustal mantle are inferred from seismic tomography. The model uses depth-dependent viscosity, and lateral variations due to temperature dependence below depth 219 km, and the distinction between (thicker) cratons, thinner lithosphere elsewhere and weak plate boundaries above that depth. They showed that the fit can be improved if, in addition to densities inferred from tomography, a negative buoyancy between zero and about -40 kg/m^3 is added in continental lithosphere, in particular in cratons (Fig. 12). The exact amount depends on model specifics, especially which crustal and tomography models are used. In their model, this buoyancy is added in the entire lithosphere, however, in reality, chemical buoyancy may be prevalent in certain depth regions. To address that issue they follow an approach similar to Wang et al. (Nature Geoscience, 16, 637–645, 2023) and plot the difference between dynamic topography from only sub-lithospheric density anomalies, and residual topography after only subtracting crustal isostatic topography against lithosphere thickness derived from tomography. The slope of this plot gives an indication of lithospheric density anomalies. For their best-fitting combination of dynamic and residual topography, they find a break in slope from nearly zero above 150 km to a negative slope below. This indicates that chemical density anomalies that cause lithospheric buoyancy are concentrated in the upper ∼150 km.

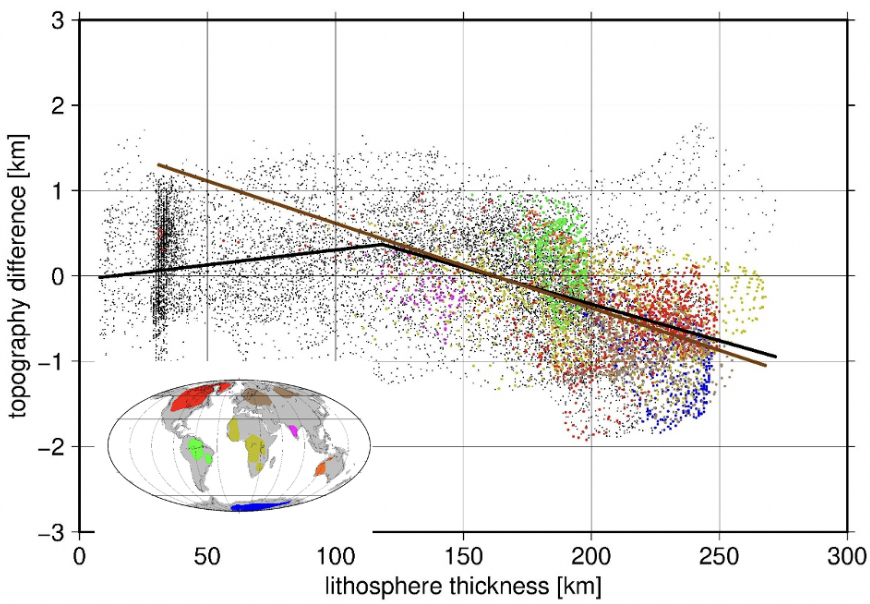

Fig. 12. Difference residual minus dynamic topography versus lithosphere thickness, with best-fitting lines to cratons (brown) and all continental lithosphere (black). Data for individual cratons are plotted with different colors, for all other points on continents in black. Densities in continental lithosphere are set to zero (i.e. global mean).

Publications

Selected oral and poster presentations

Apeh OI, Tenzer R, Pham LT, Moka EC, Onah EU (2024) A rock density model for geodynamic and tectonic studies of the Southern Benue Trough of Nigeria from a tailored gravity data. Session: GD6.1 – Structure, deformation and dynamics of continental crust and upper mantle, and the nature of mantle discontinuities. General Assembly of the European Geosciences Union, Vienna, Austria, 14-19 April, 2024.

Apeh OI, Tenzer R, Pham LT, Moka EC, Onah EU (2023) Mapping of a thick sedimentary cover for mineral exploration at the Southern Benue Trough of Nigeria from

a synthetic Bouguer gravity data. AGU Annual Meeting, San Francisco, USA, 11-15 December 2023.

Bagherbandi M (2024) Preliminary results of the GRACE and GRACE Follow-on derived land uplift model in Fennoscandia. the Nordic Geodetic Commission (NKG) Science Week, Reykjavik, ICELAND 12-14 March 2024.

Bagherbandi M, Sjöberg LE (2024) GIA related surface gravity vs. height changes using GRACE and GRACE-Follow on data in Fennoscandia. 20th International Symposium on Geodynamics and Earth Tides. August 25-30, 2024, University of Strasbourg, France.

Bagherbandi M (2025) Relationship between surface gravity and height changes due to glacial isostatic adjustment using GRACE and GRACE-FO in Fennoscandia and Canada. 49th NKG Working Group of Geodynamics and Earth Observation. Kartverket Oslo Norway, 11-13 March 2025.

Bagherbandi M, Sjöberg LE, Foroughi I, Abd El-Gelil M (2025) Investigating Surface Gravity and Height Variations due to Glacial Isostatic Adjustment: Insights from GRACE and GRACE-FO Data in Fennoscandia and Canada, EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-2238, https://doi.org/10.5194/egusphere-egu25-2238,2025.

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Ma Z, Tenzer R, Hok-Sum F (2024) Estimating the Mass Sea level from GRACE using Spherical Slepian Functions - A Case Study in the South China Sea. The 10th International Conference on Water Resource and Environment (WRE 2024). Hong Kong, 15-18 December, 2024.

Ma Z, Tenzer R, Hok-Sum F (2024) Estimating spatio-temporal characteristic of the mass sea level variation of the South China Sea using Spherical Slepian functions. Session: G4.1 - Satellite Gravimetry: Data Analysis, Results and Future Mission Concepts. General Assembly of the European Geosciences Union, Vienna, Austria, 14-19 April, 2024.

Steinberger B, Cui R (2025) Modeling geoid and dynamic topography from tomography-based thermo-chemical density anomalies in the lithosphere and convecting mantle beneath, EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-884.

Zou F, Tenzer R, Ma Z (2024) Analysis of the mean sea level variations in Hong Kong. The 10th International Conference on Water Resource and Environment (WRE 2024). Hong Kong, 15-18 December, 2024.

Zou F, Tenzer R, Ma Z (2024) Water storage variations in Tibet from GRACE and hydrological data. The 10th International Conference on Water Resource and Environment (WRE 2024). Hong Kong, 15-18 December, 2024

Selected peer-reviewed publications

Apeh OI, Tenzer R, Pham LT, Kemgang Ghomsi FE, Ribeiro-Filho N (2024) New insights into crustal and geological structures beneath the Southern Benue trough of Nigeria and parts of Cameroon Volcanic Line from tailored gravity data. Physics and Chemistry of the Earth 133: 103540.

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JSG T.43 Statistical methods in regional gravity field modelling

Chair: Mehdi Eshagh (Sweden-Czech Republic)
Affiliation: Commission 1,2, IGFS

Members:
Michal Šprlák (Czech Republic)
Juraj Janák (Slovakia)
Peiliang Xu (Japan)
Pavel Novák (Czech Republic)
Lorant Földváry (Hungary)
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Riccardo Barzaghi (Italy)
Robert Tenzer (China-Hong Kong)
Dimitrios Tsoulis (Greece)
Ismael Foroughi (Canada)
Majid Abrehdary (Sweden)
Petr Vaníček (Canada)
Ling Yang (China)
Ryan A. Hardy (USA)

Activities of the group

This report summarises the key activities of the study group carried out between 2023 and 2025. The work focused on advancing theoretical and practical aspects of physical geodesy, with an emphasis on uncertainty estimation, far-zone effects, spectral combination methods, and geoid determination. A brief overview of the main outcomes is presented below, organised by topic.

Achievements and Results

Studies

Downward continuation, Uncertainty Estimation and Error Propagation
Novák et al. (2024) examined integral-based mathematical models to solve geodetic boundary value problems (BVPs), focusing on transforming the gradients of the disturbing potential into the potential itself. Two model types were studied: (1) Spherical BVPs using grouped disturbing gradients up to third order (2) Individual gradients as Fredholm integral equations of the first kind. Both are made practical via surface integral discretisation, though additional regularisation is often needed. Covariance laws support the integral formulas, while least-squares with regularisation is applied to the integral equations to derive error variance–covariance matrices (EVMs). Numerical examples demonstrate EVM construction based on gradient errors. The study combines stochastic and deterministic modelling, supported by closed-loop tests with

synthetic data and external validation using independent reference values—addressing a key gap in physical geodesy Eshagh et al. (2025) evaluated four methods—Direct Inversion (DIR), Remove-Compute-Restore (RCR), Truncation Reduction (TR), and Modified Integral Inversion (MII)—to invert GOCE satellite gradient data into 30 arc-minute surface gravity anomalies over Central Europe. The methods were assessed by signal-to-noise ratio (SNR), error propagation, and regularization. RCR had the lowest SNR due to missing long-wavelength signals. Although uncertainties in these long-wavelength reductions are large, their influence is minor compared to GOCE data noise. RCR and TR remove signal components differently: RCR via spectral truncation, TR via spatial splitting. MII provides an optimal balance between EGM truncation and domain size. All methods use stochastic models with Tikhonov regularization and biased and unbiased variance–covariance matrices. MII showed the best uncertainty realism, while DIR, TR, and MII propagated the GOCE gradient errors better than RCR.

Far-Zone Effects in Spherical Integral Transformations

Integral transformations are key tools in gravity field modelling. Global data coverage is assumed, but in practice only partial data are available. The global integral is split into: (1) Near-zone effect via numerical integration within a spherical cap (2) Far-zone effect using harmonic expansions beyond the cap. Although near-zone effects are evaluated numerically, far-zone contributions require precise theoretical quantification. This has been extensively studied for isotropic transformations like Hotine's, Poisson's, and Stokes's formulae. Šprlák and Pitoňák (2024a) reviewed the theory of far-zone effects in transformations of disturbing potential and its derivatives—radial, horizontal, and mixed up to third order. In a follow-up (2024b), they advanced geodetic methodology by deriving far-zone effects for two types of spherical transformations: (1) Analytical solutions of horizontal and mixed BVPs, including higher-order vertical derivatives, (2) Spatial derivatives (vertical, horizontal, or mixed) of these solutions up to third order. These formulas were implemented in MATLAB and validated through closed-loop simulations. Truncation errors were also analysed via harmonic expansions. Pitoňák et al. (2025) developed a MATLAB library for computing far-zone effects on gradients up to third order. The library includes scripts for calculating integral and error kernels, truncation coefficients, and far-zone effects for selected parameters. The tool, FarZone4IT, was extensively tested and validated by Belinger et al. (2024b) and Trnka et al. (2024). The MatLab-based software library FarZone4IT consists of a series of publicly available scripts via the following link https://gitlab.com/integral_transformation/farzone4it Also, FarZone4IT is an indispensable tool for the upward/downward continuation of gravitational field quantities, in terrestrial, airborne, and satellite data combination, validation, and geophysical interpretation.

Spectral combination

Spectral combination refers to combining geodetic data based on their frequency content, rather than combining the signals directly in the spatial domain. Pitoňák et al. (2023a) applied a spectral combination method to estimate height anomalies from gradients of the gravitational potential measured by satellites. The method solves boundary value problems (BVPs) in spherical approximation, using gradients up to the third order. Synthetic gradients were generated from a global geopotential model, allowing for closed-loop testing. Results showed that horizontal derivatives of the potential have a greater influence on the estimated height anomalies than vertical derivatives. Pitoňák et al. (2023b) examined the use of the Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite data, particularly the official Level 2 product `GRD_SPW_2`, in estimating height anomalies over two test areas in Central and Northern Europe (Czech Republic/Slovakia and Norway). GOCE measured second-order derivatives of the gravitational potential with high accuracy and near-global coverage. A spectral weighting model was used, with weights estimated to validate the gradient data. The model continues the gradients from GOCE's orbital altitude down to the Earth's surface and converts them into height anomalies in a single computational step. Errors of the downward continuation were estimated using closed-loop tests. For comparison with Global Navigation Satellite Systems (GNSS)/levelling reference data, both the satellite gradients and reference values were corrected for systematic effects such as tide system differences. The high-frequency part of the signal, which is attenuated in satellite data, was removed from the reference values. Results showed significant improvements in height anomaly accuracy: the accuracy improved by up to 48% in Czech Republic/Slovakia and 55% in Norway when comparing Release 6 to Release 2 of the gradient grids. The absolute accuracy of `GRD_SPW_2` Release 6 achieved standard deviations of 8.7 cm and 9.3 cm over Czech Republic/Slovakia and Norway, respectively.

Geoid Determination and Practical Applications

Gerlach and Rummel (2024) studied error propagation in classical gravity field methods such as spherical splines, least-squares collocation, and Stokes's formula. They explored whether levelling data could enhance gravity field models. Using a synthetic test case (UELN network in Central Europe), two scenarios were tested: (i) combining potential differences from levelling and a geoid model in a network adjustment, and (ii) using levelled potential differences as additional observations in regional geoid modelling. Results showed that including levelling data (i) improves GNSS-based height networks by ∼40%, and (ii) reduces regional geoid model errors by ∼20% at levelling benchmarks. Though results depend on the stochastic model, the approach ensures consistency between levelling and geoid-based height systems. The method also applies to chronometric or hydrodynamic levelling.

Foroughi et al. (2023) addressed internal geoid error estimation. They presented formal error propagation for gravity data and models through a regional geoid computation method combining the inverse Poisson equation and Hotine transform in Helmert space (the "one-step integration method"). Tests in the challenging Colorado region used ground and airborne gravity data, a digital terrain model (DTM), and a global EGM for long wavelengths. Foroughi et al. (2024) analysed the horizontal components of airborne gravity, which relate to vertical deflection and gravity field slope. Using the one-step integration method, they solved a weighted least-squares system using all three components of the airborne gravity vector. Tests in Colorado showed that incorporating horizontal components allows increasing flight line spacing by ∼40%, significantly reducing costs while maintaining geoid height accuracy.

At the National Geodetic Survey (NGS), significant effort has been put into error propagation of a 1 arcminute gravity error grid with intra-grid correlations into geoid errors for GEOID2022. Two-dimensional FFT methods were devised to propagate gravity errors into geoid errors without redundant computations or excessive memory use. Additionally, local linear approximations were made to verify these results. The final error grids were calibrated against the Geoid Slope Validation Survey (GSVS) GNSS/levelling, and uncertainties of ∼1 cm over open ocean, 1–2 cm over CONUS, 2–3 cm over parts of CONUS at high elevation or with poor data coverage, and 2–6 cm over Alaska and the Canadian Rockies were found. Due to limitations in the assumptions used to generate these grids, it is suspected that the errors may be somewhat conservative or pessimistic in CONUS, but optimistic in more remote or rugged settings.

Publications

Selected oral and poster presentations

Belinger J, Pitoňák M, Novák P, Šprlák M (2024) Estimation of Global Root Mean Square Error of Geoid Height Calculated by Integral Transforms. International Conference - Satellite Methods in Theory and Practice, February 1, Brno, Czech Republic (in Czech).

Belinger J, Pitoňák M, Trnka P, Novák P, Šprlák M (2024) Estimation of the Global Root Mean Square Error of Selected Gravitational Field Functionals Calculated by Integral Transforms. Poster presented at the European Geosciences Union General Assembly, April 14-19, Vienna, Austria.

Belinger J, Pitoňák M, Novák P, Šprlák M (2024) Estimation of Global Root Mean Square Error of Geoid Height Calculated by Integral Transforms. International Conference - Satellite Methods in Theory and Practice, February 1, Brno, Czech Republic (in Czech).

Belinger J, Pitoňák M, Trnka P, Novák P, Šprlák M (2024) Estimation of the Global Root Mean Square Error of Selected Gravitational Field Functionals Calculated by Integral Transforms. Poster presented at the European Geosciences Union General Assembly, April 14-19, Vienna, Austria.

Belinger J, Trnka P, Šprlák M, Pitoňák M, Novák P (2023) Implementation and Testing of the Software Library for Calculating Far Zone Effects of the Spherical Integral Transformations. XXVII Czech - Slovak - Polish Geodetic Days. May 25-27, Sobotín, Czech Republic (in Czech).

Foroughi I, Goli M, Pagiatakis S D, Ferguson S (2023, December) The power of airborne vector gravimetry for more accurate geoid models. In: *AGU Fall Meeting Abstracts*, Vol. 2023, pp. G32A-02.

Foroughi I, Goli M, Pagiatakis S, Ferguson S (2023) Contribution of the horizontal components of airborne vector gravity measurements in geoid determination. In: *XXVIII General Assembly of the International Union of Geodesy and Geophysics (IUGG)*. GFZ German Research Centre for Geosciences.

Pitoňák M, Belinger J, Novák P, Šprlák M (2025) Downward Continuation of the Gravitational Gradient Components to Gravitational Field Quantities by Spheroidal Spectral Combination Technique. European Geosciences Union General Assembly, April 27 - May 2, Vienna, Austria.

Pitoňák M, Šprlák M, Belinger J, Novák P (2024) A Theoretical Study on the Spectral Combination of Vertical and Horizontal Spheroidal Boundary-Value Problems. 13th Slovak Geophysical Conference, September 11-12, Bratislava, Slovakia.

Pitoňák M, Šprlák M, Belinger J, Novák P (2024) Spectral Combination of Vertical and Horizontal Spheroidal Boundary-Value Problems: A Theoretical Study. Gravity, Geoid and Height Systems 2024, Joint IAG Commission 2, IGFS and GGOS Symposium, September 4-6, Thessaloniki, Greece.

Novák P, Šprlák M, Pitoňák M (2023) Stochastic Modelling Applied to Integral Transforms of Physical Geodesy. 28th IUGG General Assembly, July 11-20, Berlin, Germany.

Novák P, Šprlák M, Pitoňák M (2024) Geodetic Boundary-Value Problems for New Types of Gravity Field Observables. 34th Conference on Mathematical Geophysics, June 2-7, Bombay, India.

Novák P, Šprlák M, Pitoňák M (2023) On Uncertainties Associated with Integral Transformations of Gravity Gradients. Poster presented at the AGU Fall Meeting, December 11-15, San Francisco, USA.

Pitoňák M, Šprlák M, Belinger J, Novák P (2024) A Theoretical Study on the Spectral Combination of Vertical and Horizontal Spheroidal Boundary-Value Problems. 13th Slovak Geophysical Conference, September 11-12, Bratislava, Slovakia.

Pitoňák M, Šprlák M, Belinger J, Novák P (2024) Spectral Combination of Vertical and Horizontal Spheroidal Boundary-Value Problems: A Theoretical Study. Gravity, Geoid and Height Systems 2024, Joint IAG Commission 2, IGFS and GGOS Symposium, September 4-6, Thessaloniki, Greece.

Pitoňák M, Šprlák M, Novák P (2023) A Theoretical Study on Local Gravitational Field Modelling by the Spectral Combination of Satellite Higher-Order Radial Derivatives and a GGM. 28th IUGG General Assembly, July 11-20, Berlin, Germany.

Pitoňák M, Šprlák M, Novák P (2023) Regional Gravitational Field Modelling by the Spectral Combination of Satellite Higher-Order Radial Derivatives of the Gravitational Potential and a Global Geopotential Model. European Geosciences Union General Assembly, April 23-28, Vienna, Austria.

Pitoňák M, Šprlák M, Ophaug V, Omang OCD, Novák P (2023) Validation of Satellite Gravitational Gradients Grids by Spectral Combination Method and GNSS/Levelling Data Over Norway, Czech Republic and Slovakia. International Seminar - Satellite Methods in Geodesy and Cadastre, February 1, Brno, Czech Republic (in Slovak).

Pitoňák M, Trnka P, Belinger J, Novák P, Šprlák M (2024) FarZone4IT: A New Software for the Calculation of Far-Zone Effects for Spherical Integral. Poster presented at the European Geosciences Union General Assembly, April 14-19, Vienna, Austria.

Pitoňák M, Trnka P, Belinger J, Novák P, Šprlák M (2024) FarZone4IT: MatLab

Software for Calculating Far-Zone Effects in Spherical Integral Transformations. 13th Slovak Geophysical Conference, September 11-12, Bratislava, Slovakia.

Pitoňák M, Trnka P, Belinger J, Novák P, Šprlák M (2024) A Novel MatLab-Based Software Library for the Calculation of Far-Zone Effects for Spherical Integral. Gravity, Geoid and Height Systems 2024, Joint IAG Commission 2, IGFS and GGOS Symposium, September 4-6, Thessaloniki, Greece.

Šprlák M, Pitoňák M, Trnka P, Belinger J, Novák P (2023) Far-Zone Effects for Integral Transformations: Theoretical and Numerical Aspects. 28th IUGG General Assembly, July 11-20, Berlin, Germany.

Trnka P, Belinger J, Šprlák M, Pitoňák M, Novák P (2023) A New Software Library for Calculation of the Far Zone Effects for Spherical Integral Transformations. 28th IUGG General Assembly, July 11-20, Berlin, Germany.

Trnka P, Belinger J, Šprlák M, Pitoňák M, Novák P (2023) Far Zone Effects for Integral Transformations: Theory and Implementation. International Seminar - Satellite Methods in Geodesy and Cadastre, February 1, Brno, Czech Republic (in Czech).

Trnka P, Pitoňák M, Belinger J, Šprlák M, Novák P (2024) An Application for Calculating Global Mean Squared Errors of Gravity Field Quantities by Integral Transformations. XXVIII Slovak-Polish - Czech Geodetic Days. May 30 - June 1, Trnava, Slovakia (in Czech).

Trnka P, Pitoňák M, Belinger J, Novák P, Šprlák M (2024) A New Software for Calculation of Far-Zone Effects for Spherical Integral Transformations. International Conference - Satellite Methods in Theory and Practice, February 1, Brno, Czech Republic (in Czech).

Trnka P, Pitoňák M, Belinger J, Šprlák M, Novák P (2024) An Application for Calculating Global Mean Squared Errors of Gravity Field Quantities by Integral Transformations. XXVIII Slovak-Polish - Czech Geodetic Days. May 30 - June 1, Trnava, Slovakia (in Czech).

Selected peer-reviewed publications

Belinger, J., Pitoňák, M., Novák, P., & Šprlák, M. (2024). Estimation of Global Root Mean Square Error of Geoid Height Calculated by Integral Transforms. *Proceedings of the International Seminar - Satellite Methods in Theory and Practice*, February 1, Brno, Czech Republic, pp. 29–37. http://dx.doi.org/10.13164/seminargnss.2024.29 (in Czech).

Belinger, J., Šprlák, M., Pitoňák, M., Trnka, P., & Novák, P. (2024). Implementation and Testing of Software Library for Calculation of the Far-Zone Effects for Spherical Integral Transformations. *Geodetický a kartografický obzor*, **70**(6), 101–109. (in Czech).

Eshagh M., Pitoňák M., Novák P. (2025). Uncertainty propagation through integral inversion of satellite gradient data in regional gravity field recovery. *Journal of Geodesy*, **99**, 18. https://doi.org/10.1007/s00190-024-01929-z.

Foroughi I., Goli M., Ferguson S., Pagiatakis S. (2024). Optimizing Airborne Flight Line Spacing for Geoid Determination with Full Gravity Vectors. In: *International Association of Geodesy Symposia*. Springer, Berlin, Heidelberg. https://doi.org/10.1007/1345_2024_253.

Foroughi I., Goli M., Pagiatakis S., Ferguson S., Novák P. (2023). Data requirements for the determination of a sub-centimetre geoid. *Earth-Science Reviews*, **239**, 104326. https://doi.org/10.1016/j.earscirev.2023.104326.

Gerlach C., Rummel R. (2024). Benefit of classical leveling for geoid-based vertical reference frames. *Journal of Geodesy*, **98**, 64. https://doi.org/10.1007/s00190-024-01849-y.

Novák P., Eshagh M., Pitoňák M. (2024). Uncertainties associated with integral-based solutions to geodetic boundary-value problems. *Journal of Geodesy*, **98**, 54. https://doi.org/10.1007/s00190-024-01858-x.

Pitoňák, M., Šprlák, M., & Novák, P. (2023). Estimation of Height Anomalies from Gradients of the Gravitational Potential Using a Spectral Combination Method. In: *International Association of Geodesy Symposia*. Springer, Berlin, Heidelberg. https://doi.org/10.1007/1345_2023_194

Pitoňák, M., Belinger, J., Novák, P., & Šprlák, M. (under review). Spectral combination of vertical and horizontal spheroidal boundary-value problems: A theoretical study. *Gravity, Geoid, and Height Systems 2024. International Association of Geodesy Symposia*

Pitoňák M., Šprlák M., Ophaug V., Omang O.C.D., Novák P. (2023). Validation of Space-Wise GOCE Gravitational Gradient Grids Using the Spectral Combination Method and GNSS/Levelling Data. *Surveys in Geophysics*, **44**(3), 739–782. https://doi.org/10.1007/s10712-022-09762-9.

Pitoňák M., Trnka P., Belinger J., Šprlák M. (2025). FarZone4IT: A MatLab-Based Software for the Calculation of Far-Zone Effects for Spherical Integral Transformations. *Earth Science Informatics*, **18**(1), 54. https://doi.org/10.1007/s12145-024-01529-7.

Šprlák M., Pitoňák M. (2024). Far-Zone Effects for Spherical Integral Transformations I: Formulas for the Radial Boundary Value Problem and Its Derivatives. *Surveys in Geophysics*, **45**(3), 977–1009. https://doi.org/10.1007/s10712-023-09818-4.

Šprlák M., Pitoňák M. (2024). Far-Zone Effects for Spherical Integral Transformations II: Formulas for Horizontal Boundary Value Problems and Their Derivatives. *Surveys in Geophysics*, **45**(5), 1663–1713. https://doi.org/10.1007/s10712-024-09842-y.

JSG T.44: Atmospheric coupling studies

Chair: Andres Calabia Aibar (Spain)
Vice-Chair: Binod Adhikari (Nepal)
Affiliations: Commission 4, GGOS (GSWR)

Members:
Yury Yasyukevich (Russia)
Anoruo Chukwuma (Nigeria)
Munawar Shah (Pakistan)
Astrid Maute (USA)
Gang Lu (USA)
Naomi Maruyama (USA)
Christine Amory-Mazaudier (France)
Ayomide Olabode (Germany)
MD Rodriguez Frias (Spain)
Nadia Imtiaz (Pakistan)
Aurora Segrelles (Spain)
Virginia Klausner de Oliveira (Brazil)
Yan Xiang (China)
Ashok Silwal (Nepal)
Mohamed Freeshah (Egypt)

Activities of the group

Atmospheric coupling studies investigate the intricate interactions between solar drivers and the Earth's upper atmosphere. The connection between solar drivers and the Earth's magnetosphere, ionosphere, and thermosphere (MIT) system is very complex and dependent on many processes, including energy-absorption, ionization, and dissociation of molecules due to variable X-ray and Extreme Ultraviolet (EUV) solar radiance. Moreover, the variable solar wind plasma combined with a favorable alignment of the Interplanetary Magnetic Field (IMF) can produce auroral particle precipitation at high latitudes, causing enhanced chemical reactions, electric currents, and Joule heating.

The primary objective of JSG4 is to enhance our understanding of the interactions between solar wind and Earth, focusing on the atmospheric coupling processes within MIT and the lower atmosphere. Consequences of the upper atmosphere conditions on human activity underscore the necessity to better understand and predict atmospheric coupling processes and prevent society from detrimental impacts on existing technologies. For instance, the propagation of electromagnetic radio waves employed by satellite communication systems depends on the spatial gradients of charged particles in the ionosphere (mostly free-moving electrons), and unforeseen anomalies can perturb technologies based on, for example, Remote Sensing (RS) or GNSS measurement data. Another impact on society involves the expansion/contraction of the atmosphere in response to the variable solar activity, producing aerodynamic drag perturbations on LEO satellites, and making satellite tracking difficult, decelerating LEO orbits, reducing their altitude, and shortening the lifespan of space assets. Therefore, the primary goal of JSG4 is to enhance our understanding of the interactions between solar wind and Earth, focusing on the coupling processes within the MIT system. In addition, waves from the lower atmosphere including atmospheric tides and planetary waves can feed into ionospheric electrodynamics, and consequently to the MIT system. For instance, gravity waves can deposit momentum in the upper atmosphere and change the mean state which then influences the wave propagation of larger waves. To that end, our tasks are to exploit the knowledge of the atmospheric coupling processes by examining multiple types of MIT measurement data. The final outcome will help to enhance the predictive capability of empirical and physics-based models through interrelating and exploring dependencies of variability between essential geodetic variables.

This report summarizes the key activities of the study group carried out between 2023 and 2025.

Achievements and Results

Studies

Integrated Earth Coupling Studies
Investigating the effects of solar wind on Earth's upper atmosphere and evaluating the importance of coupled processes in the MIT system based on physical laws and principles such as continuity, energy and momentum equations and solving partial differential equations. This includes studying the coupling processes within the MIT system, associated with diurnal, seasonal, and solar wind drivers, as well as the lower atmosphere forcing. In addition, waves propagating from the Earth's surface related to natural and anthropogenic hazards will be investigated.

Predictive Modelling
Developing predictive models to forecast the effects of solar wind on Earth's upper atmosphere. To increase the accuracy of predictive models, the approach employs cross-validation using observational data and numerical simulations. Discrepancies between in situ measurements and model outputs reveal areas where coupling processes, such as magnetosphere-ionosphere energy transfer and thermospheric feedback mechanisms, require more precise description.

Data Sharing
Creating a web platform for sharing data and model products that are freely available for the scientific community. This will foster collaboration, accelerate research in this field, and help to achieve the above objectives. Currently, there are several centers and agencies dedicated to space weather research and forecasting.

International Cooperation and Scientific Dissemination
Enhancing international cooperation by sharing knowledge and research tools, organizing workshops and sessions at international conferences, co-supervising students, and helping to improve manuscripts and projects. Encouraging interdisciplinary research initiatives and collaboration between public and private institutions can foster

innovation and development of new technologies for space weather monitoring and prediction.

Projects

Electrodynamics at High Latitudes
The interaction of the solar wind with the Earth's magnetosphere has a significant impact on the high-latitude ionosphere. The Joule heating (JH), Field Aligned Currents (FACs), and electric and magnetic potentials at polar caps are utilized to evaluate the high latitude ionosphere's response to solar wind during several case studies.

Magnetosphere-Ionosphere Coupling
The high-latitude ionosphere electrodynamics have a substantial impact on the low-latitude ionosphere via global ionospheric and magnetospheric coupling. FACs that flow along magnetic field lines connect the magnetosphere and ionosphere. Additionally, the JH, which is primarily found at high latitudes, can extend to low latitudes via various coupling mechanisms and have a substantial impact on the low-latitude ionosphere and thermosphere. These consequences include changes in thermospheric circulation and winds, the formation of TIDs, the regulation of equatorial electrodynamics, ionospheric storms, and plasma redistribution. An empirical model is used to investigate storm-time fluctuations in ionospheric electric potential, magnetic potential, FACs, and JH.

Low-Latitude Ionosphere
We plan to investigate the effects of geomagnetic storms on the low-latitude ionosphere using mechanisms such as PPEFs, disturbance dynamo effects, and thermospheric heating, which cause changes in ionospheric currents, TEC variations, changes to the EIA, and the generation or suppression of plasma irregularities.

Thermospheric Density and Winds
This work focusses on investigating the correlations between non-gravitational accelerations and atmospheric winds (both charged and neutral) using data from the CASSIOPE (CAScade SmallSat and IOnospheric Polar Explorer) satellite. His proposed study aims to utilize empirical models such as the Horizontal Wind Model 2014 (HWM14) and physics-based models like the TIEGCM to cross-validate and improve the accuracy of a new dataset and the existing models during major storm events.

Editorial activity

Preparation Special Issue at Frontiers Journal: Innovative Approaches to Atmospheric Coupling and Geodetic Space Weather Research
(https://www.frontiersin.org/research-topics/68379/innovative-approaches-to-atmospheric-coupling-and-geodetic-space-weather-research).

Sessions organization at international conferences

Preparation Session at AOGS 2025: (ST-26) Enhancing Understanding of Upper Atmosphere Coupling Processes and Their Societal Impacts (https://www.asiaoceania.org/aogs2025/public.asp?page=sessions_and_conveners.asp).

Interactions with the IAG Commissions and GGOS

Regularly exchange research ideas and concepts within the group to foster collaboration and stimulate innovative solutions. This open communication encourages active participation and supports collective growth in ongoing and future research projects.

Several online seminars were organized to facilitate knowledge exchange and keep the team updated on trends in space weather research.

Refined plans for the period of 2025-2027

Understanding atmospheric coupling across the MIT system remains a complex task due to the dynamic nature of solar-terrestrial interactions and observational limitations. The refined plans for the period 2025-2027 are as follows:

- Understanding Multiscale Coupling Mechanisms in the MIT System
- Quantifying High-Latitude Forcing Effects on Low-Latitude Ionospheric Dynamics
- Integrating Lower Atmospheric Forcing into Upper Atmosphere Models
- Mitigating the Impact of Space Weather on Critical Technologies

Publications

Selected peer-reviewed publications

Adhikari, B., Klausner, V., Candido, C.M.N., Poudel, P., Gimenes, H.M., Siwal, A., Gautam, S.P., Calabia, A., Shah, M. (2024) "Lithosphere–atmosphere–ionosphere coupling during the September 2015 Coquimbo earthquake", J Earth Syst Sci, 133, 35. https://doi.org/10.1007/s12040-023-02222-x.

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Freeshah, M., Adil, A., Şentürk, E., Zhang, X., Ren, X., Liu, H., Osama, N. (2024), A Cyclone Formation, Eastward Plume Drag, Ion-hydration Process, and the Consequent Ionospheric Changes Following the 2022 Hunga Tonga-Hunga Ha'apai Volcanic Eruption. Advances in Space Research, 73(5):2457-2470, https://doi.org/10.1016/j.asr.2023.12.029.

Freeshah, M., Şentürk, E., Zhang, X., Livaoğlu, H., Ren, X., Osama, N. (2024), Investigating Multiple Ionospheric Disturbances Associated with the 2020 August 4 Beirut Explosion by Geodetic and Seismological Data. Pure and Applied Geophysics., https://doi.org/10.1007/s00024-023-03386-9.

Freeshah, M., Osama, N., Zhang, X. (2023), Using real GNSS data for ionospheric disturbance remote sensing associated with strong thunderstorm over Wuhan city. Acta Geod Geophys 58, 553–574, https://doi.org/10.1007/s40328-023-00423-w.

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Shah, M., Shahzad, R., Jamjareegulgarn, P., Ghaffar, B., Oliveira-Júnior, J.F., Hassan, A.M., Ghamry, N.A. (2023). Machine-Learning-Based Lithosphere-Atmosphere-Ionosphere Coupling Associated with Mw > 6 Earthquakes in America. Atmosphere, 14, 1236. https://doi.org/10.3390/atmos14081236.

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JSG T.45: Dynamic gravity modelling of given distributions

Chair: Dimitrios Tsoulis (Greece)
Affiliations: Commissions 2,3

Members:
Judit Benedek (Hungary)
Georgia Gavriilidou (Greece)
Christian Gerlach (Germany)
Ropesh Goyal (India)
Michael Kuhn (Australia)
Pavel Novák (Czech Republic)
Paolo Panicucci (Italy)
Gábor Papp (Hungary)
Alberto Pastorutti (Italy)
Daniele Sampietro (Italy)
Matej Varga (Switzerland)
Jérôme Verdun (France)

Activities of the group

The members of the study group focused their research on examining new theoretical developments for expressing the gravity signal of finite mass distributions. For this purpose, they implemented and validated various different techniques by performing forward gravity modelling at different scales. Special emphasis was given on evaluating and expanding the stochastic approach for spherical harmonics of given sources. All studies embedded in the frame of mass transport and mass balance problems.

Achievements and Results

The collaboration among members led to publications in high impact journals.

Sampietro et al. (2023) defined an empirical process for the three-dimensional inversion and discussed the setting of the involved ancillary parameters. The proposed method was implemented to model the Mediterranean Sea.

Deng et al. (2024) modeled topographic and crustal masses as tesseroidal elements, based on the corresponding ETOPO1 and CRUST1.0 models, to evaluate globally the effects of their induced gravitational curvatures (third-order derivatives of the gravitational potential).

Gavriilidou et al. (2024) quantified the gravity effect of the ice melting between 2009 and 2016 on a part of Vernagtferner glacier located in Austrian Alps, using high resolution Digital Terrain Models. The polyhedral and prismatic representations of the masses were validated and compared with respect to the sensitivity of A10 absolute gravimeters.

Braitenberg et al. (2025) proposed a novel approach to identify an ophiolite body using high-resolution gravity data, by testing the hypothesis of its existance at specific depths.

Gavriilidou and Tsoulis (2024) evaluated the uncertainty propagation technique to stochastically model a source mass, using the shape of general polyhedra, and calculated gravitational potential variations using spherical harmonic coefficients.

Gavriilidou and Tsoulis (2025a) and Gavriilidou and Tsoulis (2025b) extended this procedure to compute variations in first and second order derivatives of the gravitational potential respectively, using Gottlieb and Legendre spherical harmonic expansions. The stochastic representation was tested for various shapes with different geometric characteristics.

Refined plans for the period of 2025-2027

The study group will continue its cooperation for the preparation of joint publications. Part of the research will be presented in forthcoming IAG conferences with splinter meetings and proposed sessions, i.e., in IAG Scientific Assembly 2025, Hotine-Marussi 2026, Gravity, Geoid and Height System 2026, and IUGG General Assembly 2027.

Publications

Selected peer-reviewed publications

Braitenberg C, Maurizio G, Pivetta T, Pastorutti A, Cavazza W (2025) Satellite gravity fields and the identification of accreted microplates. Geoscience Frontiers 16(2):101976, https://doi.org/10.1016/j.gsf.2024.101976.

Deng X-L, Shen W-B, Kuhn M, Hirt C, Pail R (2024) Sensing the global CRUST1.0 Moho by gravitational curvatures of crustal mass anomalies. Geo Spatial Information Science 27(2):347–363, https://doi.org/10.1080/10095020.2022.2136539.

Gavriilidou G, Gerlach C, Tsoulis D (2024) Analytical computation of local gravitational effects of mountain glacier mass change from polyhedral and prismatic modeling - test case Vernagtferner, Austrian Alps. Global and Planetary Change 234, https://doi.org/10.1016/j.gloplacha.2024.104378.

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Gavriilidou G, Tsoulis D (2025a) Stochastic modelling of polyhedral gravity signal variations. Part I: First-order derivatives of gravitational potential. Journal of Geodesy 99:22, https://doi.org/10.1007/s00190-025-01937-7.

Gavriilidou G, Tsoulis D (2025b) Stochastic modelling of polyhedral gravity signal variations. Part II: Second-order derivatives of gravitational potential. Journal of Geodesy 99:16, https://doi.org/10.1007/s00190-025-01938-6.

Sampietro D, Capponi M, Thébault E, Gailler L (2023) An Empirical Method for the Optimal Setting of the Potential Fields Inverse Problem. Geophysical Prospecting 71(2):350–365, https://doi.org/10.1111/1365-2478.13305.

JSG T.46 Deformation, rotation and gravity field modeling for Earth and space

Chair: Yoshiyuki Tanaka (Japan)
Affiliations: Commissions 2,3

Members:
Shin-Chan Han (Australia)
Hom Nath Gharti (Canada)
Guangyu Fu (China)
Isabelle Panet (France)
Volker Klemann (Germany)
Zdeněk Martinec (Ireland)
Alberto Pastorutti (Italy)
Carla Braitenberg (Italy)
Daniel Melini (Italy)
Elia Giliberti (Italy)
Giorgio Spada (Italy)
Junichi Okuno (Japan)
Taco Broerse (Netherlands)
Riccardo Riva (Netherlands)
Wouter van der Wal (Netherlands)
Peter Vajda (Slovakia)
José Fernández (Spain)
Kuanhung Chen (Taiwan)
Jeanne Sauber (USA)

Activities of the group

Over the past two years, JSG T.46 has focused on a wide range of spatiotemporal phenomena captured by recent advances in geodetic observation techniques. The group has contributed to the development and refinement of physical models, which have been applied to infer internal processes of the Earth and other planetary bodies, elucidate mechanisms of climate change, and support disaster mitigation efforts. Compared to the previous four-year period, the scope of research has expanded from local-scale variations to include broader-scale processes, encompassing phenomena such as subduction slab dynamics, core-mantle interactions, and planetary deformation (Achievements and results). Collaborative studies have been carried out to improve the usability and reliability of the software used for surface loading computations and gravity data inversion (Software developement). In addition, the developed models have been employed to enhance the accuracy of GGOS and to support the design and planning of future space missions (Interactions with the IAG Commissions and GGOS).

Achievements and Results

Studies

The following results have been selected and summarized by the chair and are not intended to be comprehensive.

Co- and post-seismic deformations
Han et al. (2024) demonstrated that the contribution of volumetric changes to the gravity signal is smaller for intermediate-depth earthquakes compared to shallow earthquakes, based on GRACE data and physical modeling. Jeon et al. (2023) demonstrated the importance of correction models for accounting for earthquake-induced effects in the estimation of hydrological mass changes using GRACE data. Huang et al. (2023a) revealed that subsidence and shoreline retreat have continued following the 2009 Samoa-Tonga earthquake by integrating InSAR, satellite altimetry, tide gauge, and GNSS data. Huang et al. (2025a) divided the post-2009 earthquake time into two different subsidence periods and documented vertical land motion rate decline initially reported by Han et al. (2019) from GRACE, GPS and other data. These findings underscore the value of such observations for future coastal risk assessment and disaster mitigation planning. Nakakoji et al. (2024) proposed a self-gravitating spherical Earth model incorporating nonlinear rheology for computing postseismic gravity changes, enabling more realistic simulations of viscoelastic relaxation processes following large earthquakes.

Earthquake cycles
Parla et al. (2025) developed a realistic three-dimensional Earth model and demonstrated that pre-seismic rapid slab extension can account for the gravity anomalies observed by the GRACE satellites just before the 2011 M9 Tohoku earthquake. D'Acquisto et al. (2023) demonstrated that the deformation characteristics of the overriding plate during the megathrust earthquake cycle differ between the interseismic and coseismic periods in subduction zones such as South America, Sunda, and northeast Japan. This study emphasized the importance of incorporating geological structures and the mechanical properties of plates into modeling. Nijholt et al. (2024) revealed the spatial and temporal characteristics of slow slip events in the North Sulawesi region of Indonesia using GNSS data. She et al. (2023) showed that seasonal variations in surface water can alter the stress state within the crust, potentially influencing seismic activity in an intraplate collision zone in China. Tanaka et al. (2025) constrained crustal fluid migration associated with an inland M7.6 earthquake in Japan using terrestrial gravity observations and GNSS data.

Volcanology
Corsa et al. (2023), Fernández et al. (2024a, 2024b), Tizzani et al. (2024) and Camacho (2024) demonstrated that advances in satellite geodetic systems such as InSAR and numerical analysis techniques including machine learning contribute to improved 4-D monitoring and predictive accuracy of volcanic activity in the field of volcano geodesy. Bódi et al. (2023a, 2023b) reanalyzed gravity change data from the Canary Islands, where signs of volcanic activity were observed during 2004-2005, using the Growth

inversion method, and constrained subsurface magmatic processes and structures.

Ground deformations, dams and mines

Zhang et al. (2025) proposed ADCMD-PolMTI method which demonstrated a practical advancement for large-scale ground deformation monitoring by automatically optimizing the trade-off between computational efficiency and performance. Yi et al. (2025) quantitatively estimated the flood discharge following the 2023 Kakhovka Dam collapse using satellite remote sensing. Fernández et al. (2024c) demonstrated that high-precision surface deformation monitoring using InSAR contributes to improved safety management in mining operations.

Core-mantle interactions

Gaugne et al. (2025) suggested that the transient north-south gravity anomaly observed near the boundary between the Atlantic Ocean and the African continent in January 2007 may have originated from a phase transition within the large low-shear-velocity province (LLSVP) beneath Africa.

GIA

Albrecht et al. (2024) simulated the feedback mechanisms during glacial cycles in Antarctica using a coupled ice sheet-solid Earth model. Irie et al. (2024) showed that lateral variations in viscosity in an Antarctic GIA model have a small impact on mass change estimates. van Calcar et al. (2023) conducted simulations of the entire glacial cycle using a fully coupled 3-D model of ice sheet-solid Earth interactions in Antarctica, and showed that this approach improves the accuracy of ice mass balance and sea-level rise predictions compared to one-dimensional models.

Marriner et al. (2023) demonstrated, based on the analysis of relative sea-level data corrected for regional GIA, that the Mediterranean Sea has experienced an approximate 24 cm rise over the past 140 years, and revealed that this rise is driven by a weakening of the Atlantic Ocean circulation. Antonioli et al. (2024) showed that an ancient fishtank on Cyprus serves as valuable benchmarks for validating GIA models, using geological and archaeological data. Williams et al. (2024) analyzed GIA in the eastern North America region using SELEN4.0 and evaluated uncertainties related to lithospheric thickness and viscosity structure through an ensemble modeling approach. Paniagua-Arroyave et al. (2024) investigated Holocene relative sea-level changes along the Caribbean and Pacific coasts of northwestern South America, demonstrating that GIA effects interact with region-specific crustal deformation.

Hijma et al. (2025) revealed, based on geological data from Doggerland in the North Sea, that two periods of rapid sea-level rise occurred around 10,300 and 8,300 years ago, driven by accelerated ice sheet melt and influxes of water from glacial lakes, with rates exceeding 1 meter per century. Klemann et al. (2024a) estimated the impact of polar motion on GIA using a three-dimensional viscoelastic Earth model and inferred the 3D rheological structure by comparing the results with GRACE-FO data.

Planetary sciences

Veenstra et al. (2024) investigated the effects of tidal heating on the rheology of

Jupiter's moon Io and gained new insights into the mechanisms of its volcanic activity and crustal deformation. Goossens et al. (2024) analyzed data from NASA's Cassini mission and revealed that Saturn's moon Titan has a low Love number k, suggesting a high likelihood of a low-density subsurface ocean that could enhance the potential habitability.

Software developement
Huang et al. (2023b) demonstrated the utility of commercial FEM for simulating GIA using a self-gravitating spherical compressible Earth model, through intercomparison with existing methods. Camacho et al. (2024) Vajda et al. (2024) and Bódi et al. (2025) expanded the applicability of the Growth inversion code, which estimates subsurface density structures from gravity data without relying on prior assumptions, and demonstrated its effectiveness in detecting shallow cavities for archaeological surveys and geophysical investigations.

Interactions with the IAG Commissions and GGOS

Shihora et al. (2025) updated the ESA ESM (Earth System Model). The new version 3.0 provides a synthetic time-variable gravity field that includes mass variations in the atmosphere, oceans, terrestrial water storage, ice sheets and the solid Earth, contributing to simulation studies for next-generation gravity missions such as GRACE-C and NGGM/MAGIC. Pastorutti and Braitenberg (2024) and Braitenberg et al. (2024) evaluated the potential of novel spaceborne gravity measurement missions utilizing quantum technology to detect various tectonic phenomena such as co- and postseismic deformations, finer lithospheric structures and the formation of seamounts. In particular, the study demonstrated the effectiveness of gravity observations in capturing mass redistributions, including aseismic displacements due to submarine volcanic activities, in offshore regions, which are difficult to observe with GNSS and InSAR. Klemann et al. (2024b) evaluated the impact of tidal mass redistribution in the atmosphere, solid Earth, and oceans on geodetic observations, and proposed optimal model selection for specific tidal constituents as well as strategies for integrating different models.
Wang et al. (2024) and Wang et al. (2025) improved the estimation accuracy of ocean tidal loading displacements by utilizing multi-GNSS observations and tidal admittance functions.
Du et al. (2023) presented applications and challenges of InSAR observations in the fields of geodynamics and engineering, highlighting both the strengths and limitations of InSAR technology and outlining directions for future research. Huang et al. (2025b) investigated the potential integration of commercial small SAR satellites into NASA's science missions focused on surface deformation, demonstrating that their high spatial resolution and rapid revisit capabilities could complement scientific investigations in fields such as cryospheric science and volcanology.

Refined plans for the period of 2025-2027

In addition to continuing our current activities, we will further enhance collaboration within the group. We plan to advance intercomparison efforts and consider the public release of software for modeling earthquake-induced deformation. We also aim to present our work at the Hotine-Marussi Symposium.

Publications

Selected oral and poster presentations

Bódi, J., Vajda, P. and Camacho, A.G. and Fernández, J. (2023a). Contributions of Growth inversion methodology to volcano gravimetry on Tenerife (Canary Islands). Paper presented at the International Workshop on Geosciences in Active Areas, Lanzarote, Canary Islands, 16-20 Oct 2023.

Braitenberg, C., Fantoni, A., Maurizio, G., and Pastorutti, A. (2024). Innovative solid Earth applications of future gravity field missions. Paper presented at the EGU General Assembly 2024, Vienna, Austria, 14-19 April 2025. https://doi.org/10.5194/egusphere-egu24-19340.

Corsa, B., Tiampo, K., Meertens, C., Anderson, K., Ellis, A., González, P.J., Fernández, J. and Sigmundsson, F. (2023). Exploring the significance of the spatial field from integrated DInSAR+GNSS time series for machine learning and volcano early warning applications. Paper presented at the International Workshop on Geosciences in Active Areas, Lanzarote, Canary Islands, 16-20 Oct 2023.

Du, S., Hu, Z., Escayo, J., Camacho, A.G., Prieto, J.F., Rodriguez, S., Davoise, D., Fernández, J. (2023). InSAR observation in Geodynamics and Engineering: some examples and challenges. Paper presented at the International Workshop on Geosciences in Active Areas, Lanzarote, Canary Islands, 16-20 Oct 2023.

Fernández, J. and Camacho, A.G. (2024a). New advances in volcano geodesy. Paper presented at the International Workshop on Space Dynamics, Satellite Geodesy, and Numerical Methods, Alicante, Spain, 30 Sep-1 Oct 2024.

Fernández, J., Du, S., Samsonov, S.V., Rodríguez, S., Tiampo, K.F. and Camacho, A.G. (2024c). Applicability of satellite radar interferometry and advanced interpretation techniques in the study of stability in mines. Paper presented at the V Mining and Mineral Hall (MMH2024), Sevilla, 15-17 October 2024.

Gaugne, C., Panet, I., Mandea, M., Greff, M., and Rosat, S. (2025). GRACE Observations of Rapid Mass Variations at the Core-Mantle Boundary During Deep Mantle Phase Transitions in Interaction with Core Flow. Paper presented at the EGU General Assembly 2025, Vienna, Austria, 27 Apr-2 May 2025. https://doi.org/10.5194/egusphere-egu25-8808.

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JSG T.47: Height datum: Definition, New Concepts, and Standardization

Chair: Xiaopeng Li (USA)
Vice-Chair: Marcelo Santos (Canada)
Affiliations: Commission 2, IGFS

Members:
Ana Cristina Matos (Brazil)
David Avalos (Mexico)
Elena Osorio-Tai (Mexico)
Fabio Albarici (Brazil)
Gabriel Guimarães (Brazil)
Georgios Vergos (Greece)
Hussein Abd-Elmotaal (Egypt)
Ismael Foroughi (Canada)
Jianliang Huang (Canada)
Juraj Janák (Slovakia)
Laura Sánchez (Germany)
Miao Lin (China)
Nicolaas Sneeuw (Germany)
Pavel Novák (Czech Republic)
Riccardo Barzaghi (Italy)
Robert Kingdon (Canada)
Yanming Wang (USA)

Associate Members:
Fernando Sansò (Italy)
Rachelle Winefield (New Zealand)

Activities of the group

The main objectives of JSG T.47 are to review and refine the definition of physical height reference surfaces, propose clear, rigorous, and manageable guidelines for their precise realization (1 cm accuracy or better), explore new theoretical models, gravity field representations, and observation technologies, including chrono-geodesy using relativistic effects, and address the standardization of height anomaly and geoid height models, especially in their seamless integration with local levelling data.

The period covered by this report includes the establishment of the joint study group. There was one online meeting and another one during the GGHS2024 – Gravity, Geoid and Height Systems Symposium – held in Thessaloniki, Greece, from 4 to 6 September 2024. They helped bring the membership closer together by discussing the objectives of the study group and defining initial tasks.

Publications

Selected oral and poster presentations

Wangmo, Dechen, Robert Kingdon, Petr Vaníček and Marcelo Santos (2025). "Deciphering Topographical Density Effects on the Relationship Between Geoid and Orthometric Height." Annual Meeting of the Canadian Geophysical Union, May 25 - 28, 2025 - Saskatoon, Canada.

Selected peer-reviewed publications

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JSG T.48: Theoretical Foundations of Machine and Deep Learning in Geodesy

Chair: Lotfi Massarweh (The Netherlands)
Vice-chair: Mostafa Kiani Shahvandi (Austria)
Affiliations: Commissions 2,3,4, GGOS (AI4G)

Members:
Alireza Amiri-Simkooei (The Netherlands)
Amir Khodabandeh (Australia)
Andrea Nardin (Italy)
Balidakis Kyriakos (Germany)
Junyang Gou (Switzerland)
Michela Ravanelli (Italy)
Mohammad M. Kariminejad (Iran)

Activities of the group

The Joint Study Group T.48 "Theoretical foundations of Machine and Deep Learning (ML/DL) in Geodesy" has been focused on investigating key theoretical aspects concerning state-of-the-art techniques more broadly in use within different geodetic domains. Two main elements are at the core of the group activities, i.e. addressing 'explainability' and 'reproducibility' when making use of ML/DL strategies. Different online meetings have taken place since the establishment of this group, including in-person meetings between members during major scientific events (e.g. EGU2025). This enabled a discussion about algorithms and methodologies, thus trying to establish a connection between *modern* Machine Learning strategies and *classical* Geodetic techniques. This joint research effort led to interesting discussions, several research outcomes, and preliminary results as discussed in the following section.

Achievements and Results

The group has been involved in several research applications, spanning over different AI techniques.

For instance, in Fuso et al. (2024), Random Forest and XGBoost, i.e. binary classification algorithms, were used to detect ionospheric perturbations from the 2015 Illapel earthquake and tsunami. The TEC perturbation time frames were manually labelled and split into training and testing datasets. The XGBoost model with a 15° elevation cut-off achieved the best performance, with an F1 score of 0.77, recall of 0.74, and precision of 0.80. It correctly identified 74.09% of slant TEC (sTEC) variations and 98.49% of non-sTEC samples. However, it misclassified 25.91% of sTEC samples and 1.51% of non-sTEC samples. The model also showed a 75-second average difference in predicting the Traveling Ionospheric Disturbances (TIDs) middle epochs, as shown in Fig.13. This work was conducted in collaboration with the Institute of Geodesy and Photogrammetry at ETH Zurich.

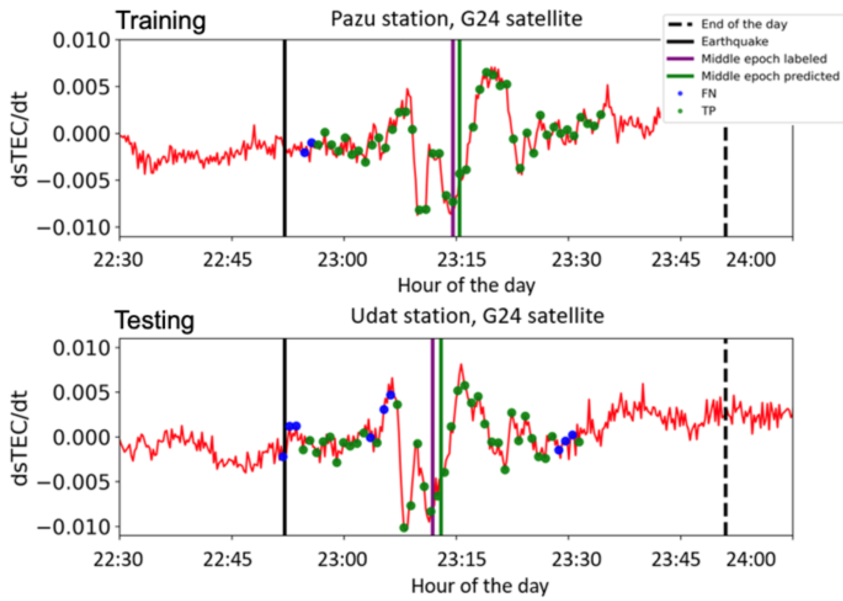

Fig. 13. Illustration of delta slant Total Electron Content (dsTEC) during training and testing, adapted from Fuso et al. (2024).

Moreover, other works such as Constantinou et al. (2023) and Ravanelli et al. (2024) have further explored innovative approaches to perform automatic real-time ionospheric perturbation monitoring and detection. In (ibid), a Gramiam Angular Difference Fields in combination with Convolutional Neural Networks (CNNs) have been used by firstly transforming time series into images, see Fig.14. These TEC estimates were computed using the Variometric Approach for Real-Time Ionosphere Observation (VARION) approach (Fratarcangeli et al. (2018)), and four tsunamigenic Earthquakes occurred in the Pacific Ocean were selected: 2010-Maule, 2011-Tohoku, 2012-Haida-Gwaii, and 2015-Illapel. The first three events are used for model training, whereas the out-of-sample validation is performed on the last one. The presented framework, highly suitable for real-time applications, achieves 91.7% of F1 score and 84.6% of recall, highlighting its potential. This approach for improving false positive detection, based on the likelihood of a TID at each time step, ensures robust and high performance as the system scales up, integrating more data for model training. This research lays the foundation for incorporating deep learning into real-time GNSS-TEC analysis, offering a joint and substantial contribution to tsunami early warning systems (TEWS) progression.

In the context of uncertainty quantification, Gou et al. (2024,) presented a comprehensive review of uncertainties of satellite-based Essential Climate Variables (ECV) using Deep Learning methods. Two specific use cases were selected for demonstrating the efficiency of DL uncertainty quantification approaches, i.e. snow cover and terrestrial water storage changes. In this way, it was possible to discuss and bridge the gap

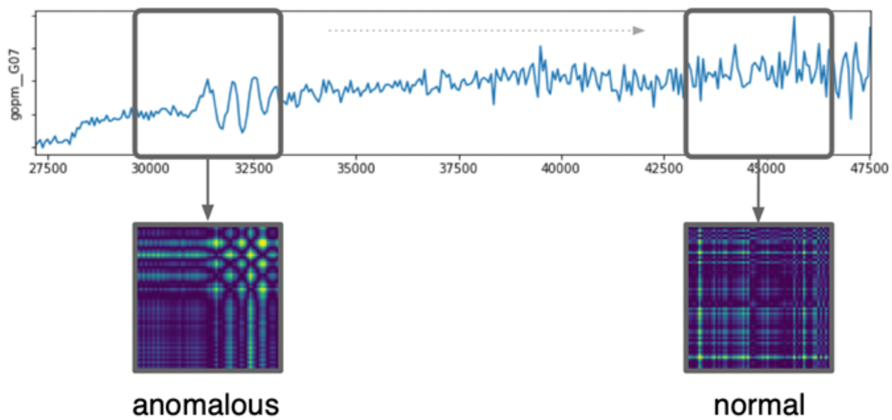

Fig. 14. Illustration of delta slant Total Electron Content (dsTEC) during training and testing, adapted from Fuso et al. (2024).

between modern methods and conventional statistical approaches, with a distinction between aleatoric and epistemic uncertainty terms. The first type is caused by data problems, including training and inference data, while the second one is related to imperfect (knowledge of) models. A Bayesian Deep Learning (BDL) approach was suggested to replace linear regression by neural network (Le Cun et al. (2015)), with the latter being formed by multiple layers with trainable parameters (i.e. weights and biases).

Further investigations with non-Gaussian distributions were proposed by Kiani-Shahvandi et al. (2025), thus introducing a Laplacian deep ensembles (LDE) method to enhance the quality of DL models and quantifying their uncertainty. A Bayesian approach is typically inefficient in this challenging task, and ensemble of models are potentially a promising alternative, however often limited to the assumption of Gaussian distribution of data. The LDE results were later demonstrated for the short-term prediction of dUT1, being the deviation of universal time (tied to Earth's rotation) from the coordinated universal time (based on atomic clocks) due to the effect of geophysical fluids (namely atmosphere, ocean, land hydrology, and sea-level variations). Similarly, in Kiani-Shahvandi et al. (2024b), short-term prediction of the Length of Day (LOD) was examined using Bayesian Hamiltonian Monte Carlo Autoencoders (BaHaMAs) for uncertainty quantification in geodetic time series. In a different work (Shavandi et al. (2024a) the short term prediction of celestial pole offsets was attempted with interpretable ML, so presenting a new methodology based on Neural Additive Models (NAMs). This work showed how NAMs predictions improve the IERS rapid products on average by 57% and 25%, respectively for dX and dY quantities under fully operational conditions.

A significant attempt to bridge the gap between modern AI solutions and classical Geodetical techniques was presented by Amiri-Simkooei et al. (2024), where DL neural networks were described in standard least-squares theory of linear models. This work was also discussed in an invited presentation at EGU2025, thus introducing a least-squares-based deep learning (LSBDL) as framework that combines the interpretability of linear least-squares theory, useful tool for parameter estimation and quality control, with the flexibility and power of deep learning. Still, a rigorous formulation of ML/DL techniques in the context of legacy Geodetic adjustment theory is far from being solved, and several further challenges arise when looking at mixed-integer models, for instance for GNSS. Still, group members at TU Delft are currently studying such problems in the Machine Learning for Ambiguity Resolution (ML4AR) project[1], which is expected to further advance the knowledge and fill theoretical gaps of ML/DL techniques in non-trivial problems like Integer Ambiguity Resolution (IAR). This activity, awarded by ESA's Navigation Innovation and Support Program (NAVISP) Element 1 programme focuses on deep neural network methods to enhance current ambiguity validation steps by data-driven approach, in particular in support to real-time precise positioning applications.

Interactions with the IAG Commissions and GGOS

This research group has established a strong interaction with other researchers from different JSGs, such as T.49 and T.50, along with preliminary collaborations with the new IAG GGSO Focus Area 'AI4G' (Artificial Intelligence for Geodesy) chaired by Benedikt Soja (Switzerland) together with his vice-chair Maria Kaselimi (Greece). In fact, together with AI4G, a Symposium J02 dedicated to 'Artificial Intelligence and Machine Learning in Geodesy' has been organized and it is scheduled for September during IAG Scientific Assembly 2025, in Rimini, Italy.

Refined plans for the period of 2025-2027

For what concerns the following two years, the study group aims at a deeper understanding and quantification of uncertainties in ML/DL models. This is not limited to parameters' estimation scenarios, but also to statistical testing problems where is not yet clear how ML/DL techniques could support or replace state-of-the-art geodetic techniques. Ultimately, the group plans to potentially organize a website page dedicated to theoretical foundations of ML/DL, thus establishing a white paper for 'safer' use of such techniques in Geodesy.

Publications

Selected oral and poster presentations

Amiri-Simkooei, A.: Theory and implementation of least-squares-based deep learning, EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May, EGU25-9878. https://doi.org/10.5194/egusphere-egu25-9878

Amiri-Simkooei, A. (2025). Invited lecture on Least-Squares-Based Deep Learning (LSBDL) at the Chinese Academy of Sciences, in Wuhan, China.

[1] https://navisp.esa.int/project/details/307/show

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JSG T.49: High-resolution probing of the troposphere and ionosphere

Chair: Michela Ravanelli (Italy)
Affiliations: Commission 4, GGOS (Geohazards Monitoring, GSWR)

Members:
Elvira Astafyeva (France)
Gregor Moeller (Austria)
Alessandra Mascitelli (Italy)
Eugenio Realini (Italy)
Lucie Rolland (France)
Szabolcs Rózsa (Hungary)
Elisabetta D'Anastasio (New Zealand)
James Foster (Germany)
Giorgio Savastano (Luxembourg)
João Galera Monico (Brasil)
Maria Virginia Mackern (Argentina)
Damian Tondaś (Poland)

Activities of the group

This document provides an overview of the main activities carried out by the ICCT Joint Study Group T.49 during the period July 2023-June 2025.
The group prioritized sharing its research outcomes through articles submitted to internationally recognized journals in the fields of geodesy and GNSS, including GPS Solutions and Advances in Space Research. Members also actively participated in key global scientific meetings—such as EGU General Assemblies, the GGOS Topical Meeting on the Atmosphere, and AGU Fall Meetings—where they presented their latest findings to the broader research community. These activities have led to the publication of several peer-reviewed papers and the delivery of numerous oral and poster presentations. This output reflects both the group's strong collaborative engagement and the relevance of their research within the scientific community.

Achievements and Results

Studies

Troposhere sounding
Troposhere sounding and analysis were focused on the possibility of having ZTD estimates from of lowcost instrumentations and/or moving platform observations as well

the impact on assimilation approaches and using tomography radio occultation methods.

Torcasio et al., 2023 studied the impact of GNSS-ZTD data assimilation on the short-term (up to 6h) forecast over Italy for the month of October 2019, using the WRF model. A dense dataset of 388 GNSS receivers was used. Results show that the forecast without data assimilation underestimates the water vapor content for the period. The GNSS-ZTD data assimilation partially compensates for this underestimation, increasing the water vapor content in the atmosphere.

Pan et al., 2023 developed a two-step machine learning pipeline for selecting data and estimating Zenith Total Delay (ZTD) using ionosphere-free Precise Point Positioning (PPP) on ($\sim 20,000$ raw GNSS files. Validated with smartphone data on ETH's rooftop, the method achieved millimeter-level ZTD accuracy in open-sky conditions. They also assessed how observation duration and multi-GNSS use impact accuracy. Applying the method to crowdsourced data in Germany, with ionospheric correction from SAPOS stations, they achieved $<$10 mm accuracy when compared to ERA5 and ML-based ZTD products. The study demonstrates that precise ZTD estimates are possible from high-quality crowdsourced smartphone GNSS data and highlights both enablers and current limitations.

Bosser et al., 2024 evaluated the CentipedeRTK network of 400 low-cost GNSS stations across mainland France for tropospheric monitoring. When compared with 186 nearby conventional GNSS stations, the low-cost stations showed strong agreement in tropospheric delay measurements (RMS difference: 9.2 mm; mean bias: 2.7 mm). Integrated Water Vapor (IWV) data from these stations also aligned well with ERA5 reanalysis (mean bias: 0.06 ± 0.82 kg/m^2; standard deviation: 1.48 ± 0.18 kg/m^2). Their effectiveness was further demonstrated during an atmospheric river event in December 2023. The study highlights the strong potential of low-cost GNSS networks for meteorological and climatological applications, particularly in under-instrumented areas.

Rózsa et al., 2023 developed a GNSS-based atmospheric sensing system in the Pannonian Basin using permanent geodetic-grade stations to estimate hourly tropospheric delays and gradients, shared via the EUMETNET E-GVAP program. They also employed tomography to reconstruct 3D refractivity models. To enhance network coverage, they tested low-cost receivers (Septentrio and u-blox F9P) for ZTD and gradient estimation. One year of data showed promising performance, with comparisons against geodetic stations, radiosondes, and ERA5 confirming the reliability of these affordable instruments for atmospheric monitoring.

Cegla et al., 2024 presented a new integrated tomography solution for GNSS meteorology is proposed to address the scarcity of observational data, particularly in the lower troposphere. This method combines ground-based GNSS observations with radio occultation (RO) excess phase in a single tomography model, thereby improving geometry and increasing data density. The methodology was validated using data from 41 GNSS stations and 78 RO profiles collected during four high-precipitation events over southern Poland. Validation against radiosonde observations and WRF reanalysis demonstrated a 20-30% reduction in RMSE for wet refractivity representation when RO data were integrated, with the final integrated product having a mean error of 3.5 ppm.

Ionosphere sounding

Ionosphere sounding and analysis were focused on the analysis of the ionospheric response to major natural hazards, using GNSS data from ground stations or CubeSats, and commercial nanosatellite constellations to monitor space weather.

Ravanelli et al., 2023 investigated the oceanic and ionospheric response in New Caledonia-New Zealand and Chile-Argentina to the 15 January 2022 Hunga-Tonga volcanic eruption, highlighting a reversed response in the oceans and in the ionosphere in terms of the amplitudes. The sea-surface fluctuations due to the passage of the atmospheric Lamb wave (i.e., air-sea wave) were not remarkable while the related ionospheric perturbation was considerable. Reversely, the eruption-induced tsunami ("regular" tsunami) caused major variations in sea-surface heights ($\sim$ 1 m near the volcano and $\sim$ 2 m along the Chilean coastline), whereas the associated ionospheric perturbation was quite small.

In this context, Han et al., 2023 used CubeSat GPS data to observe high-altitude ($>$550 km) Traveling Ionospheric Disturbances (TIDs) triggered by the Hunga Tonga-Hunga Ha'apai eruption. The CubeSats provided enhanced spatio-temporal coverage compared to ground stations, detecting large perturbations (up to 10 TECU) that propagated globally at 350 m/s with Lamb waves. Notably, TIDs were observed over Australia hours before the tsunami's arrival. The study demonstrates the value of low-cost CubeSats for monitoring Earth-ionosphere interactions and potentially improving geohazard early warning systems.

Moeller et al., 2024 present a successful in-orbit demonstration of spaceborne ionospheric tomography using single-frequency GNSS measurements from a commercial nanosatellite constellation. By implementing the GRAPHIC linear combination method in open-source software (raPPPid and ATom), we achieved sub-meter orbit estimation. The resulting ionospheric delay measurements correlated well with the TIE-GCM model, proving that low-cost nanosatellites are a viable tool for monitoring space weather and the ionospheric state. The work was presented at 2023 AGU Fall Meeting and at 15th IAA Symposium on Small Satellites for Earth System Observation, 4-8.05.2025, Berlin, Germany.

Other studies applied AI to detect ionospheric perturbations caused by earthquakes and tsunamis. Fuso et al., 2024 used supervised machine learning (Random Forest and XGBoost) to classify TEC perturbations from the 2015 Illapel earthquake and tsunami. The XGBoost model with a 15° elevation cutoff achieved the best results (F1 score: 0.77, precision: 0.80, recall: 0.74). Despite some misclassifications, the model effectively identified ionospheric disturbances with an average timing offset of 75 seconds. Ravanelli et al., 2024 developed a deep learning framework using Gramian Angular Difference Fields and Convolutional Neural Networks, transforming real-time TEC time series (from VARION) into images. Trained on three tsunamigenic events (Maule, Tohoku, Haida-Gwaii) and validated on Illapel, the system achieved an F1 score of 91.7% and recall of 84.6%, showing strong potential for real-time ionospheric perturbation detection and early warning applications.

Finally, João F. Galera Monico presented at the 2025 EGU General Assembly the GNSS NavAer project, that aims to develop a robust infrastructure for monitoring space weather, with a focus on ionospheric scintillation (IS) — rapid signal fluctuations that can impair GNSS performance. The GNSS NavAer project deploys a network of GNSS receivers to collect real-time ionospheric data, enabling the detection and characterization of ionospheric scintillation (IS) using advanced algorithms. Accessible through the ISMR Query Tool, this system supports timely responses to space weather disruptions, particularly in aviation. By fostering international collaboration and data sharing, the project enhances GNSS reliability and contributes to developing effective mitigation strategies for IS-related impacts.

Sessions organization at international conferences

E. Astafyeva co-organized the following session at 2024AGU Fall Meeting: Traveling Ionospheric Disturbances Driven from Above and from Below I Oral and SA31E - Traveling Ionospheric Disturbances Driven from Above and from Below II Poster M. Ravanelli was the chair at the Geohazards monitoring session at the GGOS Topical meeting on the Atmsophere, held in Potsdam in October 2024.

Interactions with Other IAG Bodies

There is strong interaction between JSG T.49 members and researchers from JSG T.48, GGOS GeTEWS, other IAG bodies and ITU. For instance, M. Ravanelli and L. Rolland are key contributors to GGOS GeTEWS for Oceania. E. Realini participated into the IAG WG 4.1.4 Low-Cost GNSS receiver systems Chair: Dinesh Manandhar (Japan). Beyond that, M. Ravanelli is involved in an ITU Topic Group on AI for Geodetic Enhancements to Tsunami Monitoring and Detection and is a member of the IAG ECS Representatives.

Publications

Selected oral and poster presentations

Gregor Moeller, Mona Kosary, Marcus Franz Wareyka-Glaner, Natalia Hanna, Lukas Müller, Markus Rothacher, Ionospheric mapping with single-frequency GNSS measurements from commercial nanosatellite constellations, 15th IAA Symposium on Small Satellites for Earth System Observation, 4-8.05.2025, Berlin, Germany, https://iaa2025.welcome-manager.de/

Gregor Moeller, Anne Dickmann, Lukas Müller, Simon Rondot, Spaceborne Ionospheric Tomography: A first in-orbit demonstration campaign, AGU Fall Meeting 2023, held in San Francisco, CA, 11-15 December 2023, Session: Atmospheric Sciences / Monitoring of GNSS Signals with High Sampling Rate as a Promising Means to Look Deeper in Earth's Atmosphere and Ionosphere Poster, Poster No. 2382, id. A13O-2382, https://ui.adsabs.harvard.edu/abs/2023AGUFM.A13O2382M/abstract

Monico, J. F. G., Tsuchiya, I., and Vani, B.: The INCT GNSS NavAer infrastructure for Space Weather Monitoring., EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-76, https://doi.org/10.5194/egusphere-egu25-76, 2025

Ravanelli, M., Constantinou, V., Liu, H., and Bortnik, J.: Harnessing AI in GNSS remote sensing: A Deep Learning framework for Real-Time Detection of Ionospheric Perturbations triggered by earthquakes and tsunamis , EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-16106, https://doi.org/10.5194/egusphere-egu25-16106, 2025

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Selected peer-reviewed publications

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Cegla, A., Moeller, G., Rohm, W., Kryza, M., Taszarek, M., Application of integrated GNSS tomography in observation study over the area of southern Poland, Advances in Space Research, Volume 74, Issue 8, 2024, https://www.sciencedirect.com/science/article/pii/S0273117724007786?via%3Dihub

Fuso, F., Crocetti, L., Ravanelli, M., & Soja, B. (2024). Machine learning-based detection of TEC signatures related to earthquakes and tsunamis: the 2015 Illapel case study. GPS Solutions, 28(3), 106.

Han, S. C., McClusky, S., Mikesell, T. D., Rolland, L., Okal, E., & Benson, C. (2023). CubeSat GPS observation of traveling ionospheric disturbances after the 2022 Hunga-Tonga Hunga-Ha'apai volcanic eruption and its potential use for tsunami warning. Earth and Space Science, 10(4), e2022EA002586.

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Ravanelli, M., Astafyeva, E., Munaibari, E., Rolland, L., & Mikesell, T. D. (2023). Ocean-ionosphere disturbances due to the 15 January 2022 Hunga-Tonga Hunga-Ha'apai eruption. Geophysical Research Letters, 50(10), e2022GL101465.

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JSG T.50: High-precision GNSS theory and algorithms

Chair: Dimitrios Psychas (The Netherlands)
Affiliations: Commissions 1,4

Members:
Andreas Brack (Germany)
Pengyu Hou (China)
Amir Khodabandeh (Australia)
Lotfi Massarweh (The Netherlands)
Nacer Naciri (USA)
Robert Odolinski (New Zealand)
Jacek Paziewski (Poland)
Sandra Verhagen (The Netherlands)
Kan Wang (China)
Safoora Zaminpardaz (Australia)
Baocheng Zhang (China)

Activities of the group

This report summarizes the 2023-2025 activities of the ICCT Joint Study Group T.50. Efforts centered on publishing in international journals on geodesy and GNSS (e.g., Journal of Geodesy and GPS Solutions) and presenting research findings at major international conferences (e.g., EGU General Assemblies, 3rd IAG Commission 4 Symposium). The group held online meetings to (a) identify and address key theoretical and algorithmic challenges in high-precision GNSS, and (b) foster collaboration through joint publications and international projects. These topics were further discussed during in-person interactions at international conferences.

The first topical discussion of the group focused on the LEO-aided positioning, navigation, timing, and atmosphere sensing (PNTA). Several members were invited to share their relevant work and highlight key challenges identified so far. A summary is given as follows. Centimeter-level ambiguity-resolved positioning using LEO frequency-varying phase-only measurements seems feasible, even in GNSS-challenged environments, under certain conditions: short baselines, highly stable clocks, and dm-level orbital biases. Although achieving high-precision positioning with single-receiver data can be challenging due to potential inaccuracies in the LEO satellite products, it was numerically demonstrated with real-world GNSS onboard data analyses that real-time orbital user range errors and clock precision can be less than 5 cm and 0.2 ns, respectively. However, uncalibrated satellite code biases remain an issue, since the number of ground stations tracking LEO satellites is limited, thereby restricting in-orbit calibrations. Preliminary findings indicate rapid positioning convergence for different user-selected observation models.

Achievements and results

Studies

Some of the research outcomes of the group members are listed below.

Role of PPP-RTK corrections' influential factors in high-precision positioning
Psychas et al. (2024) studied the intricacies inherent in multi-epoch filtered PPP-RTK corrections. Next to the consequences of the corrections' dependency on the network's S-basis choice, the study analyzed the role of the corrections' latency and time-correlation for multi-epoch user positioning. Along similar lines, Hou et al. (2024) analyzed the precision discrepancy of ambiguity-float combined corrections between pivot and non-pivot receivers and the relevant user-impact. It was shown that one can dispense with the pivot-receiver dependency and ensure homogeneity in user positioning once network integer ambiguity resolution is achieved.

New filter formulations for GNSS data processing
In an attempt to limit the precision loss associated with the multi-epoch PPP-RTK parameter solutions under a misspecified user stochastic model, Khodabandeh et al. (2023) proposed an alternative formulation of the user Kalman-filter. This new formulation was shown to deliver close-to-minimum-variance filtered solutions under certain conditions. The applicability of this strategy was extended by Ke et al. (2024) to a multi-station provider using an ionosphere-weighted model that avoids duplicated constraints. Hou et al. (2024) introduced a generalized least-squares filter, as an extension of the generalized Kalman filter Teunissen et al. (2021), in allowing the number of the linked-in-time parameters to vary over time when one is solely interested on their estimation.

Estimation+testing considerations for accurate confidence regions
Zaminpardaz and Teunissen (2024) demonstrated that the customary confidence regions obtained from an estimator, which neglects the impact of testing on estimation, are incorrectly describing the resultant estimator's quality. To this end, they explored the interaction between estimation and testing, and presented how one can produce truthful confidence regions by using the non-normal distribution characterizing the combined estimator.

LEO-aided PNTA
In view of the need for providing positioning users with LEO satellite products, Xie et al. (2024) assessed the real-time Kalman filter-based clock estimation performance for Sentinel-3B, by introducing its predicted orbits as constraints. It was numerically demonstrated that a signal-in-space ranging error better than 8 cm can be achieved. Wang et al.(2024) and Massarweh and Verhagen (2025) studied the LEO-enhanced ionosphere-float PPP-RTK positioning performances with simulated measurements from *navigation-oriented* LEO satellites and confirmed convergence times of less than 5 min (90%) in a GPS+LEO setup. Through a feasibility analysis, Yang et al. (2025) demonstrated that centimeter-level ambiguity-resolved positioning using frequency-varying phase-only signals from *communication-oriented* LEO satel-

lites is also possible under certain conditions. The advantages of using measurements from LEO satellites were also shown in the frame of electron density reconstruction, for which Schreiter et al. (2024) provided insights for further improving ionospheric modeling.

Integer least squares: bias-constrained estimator and dual mixed-integer models
Khodabandeh and Teunissen (2024) proved that the BEAT method, as developed in Khodabandeh (2022), offers 'best' estimation of the integer- and bias-parts of the bias-affected float ambiguity vector, and then applied it for GLONASS single-differenced ambiguity resolution. Teunissen and Massarweh (2024) presented the dual mixed-integer least-squares formulation and its advantages, and proposed two approximations to reduce the computational burden of the implicit integer least-squares problem.

Low-cost precise (non-)positioning applications
Odolinski et al. (2024) assessed the multi-GNSS RTK performance in baselines formed by Android smartphones. Centimeter-level positioning and ∼100% ambiguity success rates were achieved for both single- and multi-epoch models. Yi et al. (2024) evaluated the PPP performance in urban environments using smartphone GNSS/IMU measurements and Galileo HAS corrections. Through vehicle experiments, it was demonstrated that the resultant performance is comparable to that achieved with four-constellation measurements and ultra-rapid products. Paziewski et al. (2025) studied and presented how low-cost GNSS and accelerometer measurements can jointly enable precise small-scale vibration monitoring, revealing that mm-level accuracy on dynamic displacements is possible. Krzan et al. (2024) and Dawidowicz et al. (2025) revealed a two-to-threefold decrease in positioning performance with low-cost antennas compared to high-quality equipment. However, selected low-cost antennas can meet the requirements of precise surveying applications under specific conditions.

Sessions organization at international conferences

- Co-organization of the session *High-precision GNSS: methods, open problems, and geoscience applications* at the EGU General Assembly 2024 & 2025 (J. Paziewski).
- Co-organization of the session *Applications of low-cost, mass-market and consumer-grade GNSS in geoscience* at the EGU General Assembly 2025 (R. Odolinski).

Editorial activity

- New Topical Collection of GPS Solutions on *Next-generation PNT: From LEO to Lunar and Beyond* (D. Psychas, A. Khodabandeh, A. Brack)
- Special Issue of Sensors on *Advancements in GNSS Precise Point Positioning Technology and Applications* (D. Psychas, R. Odolinski)
- Journal of Spatial Science, Volume 70 on *GNSS real-time precise point positioning: algorithms, applications, and challenges* (B. Zhang, A. Khodabandeh)

Acknowledgements

The group members acknowledge and thank Meifang Wu and Lucas Schreiter for their contributions to the discussions held on LEO-aided PNTA.

Interactions with IAG Commissions and GGOS

Members of the group held discussions with researchers from WG 4.1.2 "Upcoming GNSS services for accuracy, reliability and resilience", WG 4.1.3 "LEO-PNT Systems", and WG 4.2.3 "Mass-market high-precision GNSS and applications".

Refined plans for the period 2025-2027

The group will continue its series of online and in-person discussions to jointly address ongoing challenges aligned with its research objectives. Collaborative research efforts are expected to strengthen, leading to publishable results. Many members plan to present their research findings at the IAG Scientific Assembly 2025 and at the Hotine-Marussi Symposium 2026. Interaction with Commissions 1 & 4 will be further enhanced during 2025-2027. No changes to the group's objectives or membership are currently anticipated.

Publications

Selected peer-reviewed publications

Dawidowicz, K., Paziewski, J., Stępniak, K., Krzan, G. On the applicability of low-cost GNSS antennas to precise surveying applications. Measurement Science and Technology, 36(1):016306, 2025. 10.1088/1361-6501/ad83e7.

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Schreiter, L., Brack, A., Männel, B., Schuh, H., Arnold, D., Jäggi, A. Imaging of the ionosphere and plasmasphere using GNSS slant TEC obtained from LEO satellites. Radio Science, 59(12):1–19, 2024. https://doi.org/10.1029/2024RS008058.

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