Inter-Commission Committee on Theory (ICCT)

http://icct.kma.zcu.cz

President: Pavel Novák (Czech Republic)
Vice President: Mattia Crespi (Italy)

Structure

Joint Study Group 0.10:	High-rate GNSS
Joint Study Group 0.11:	Multiresolutional aspects of potential field theory
Joint Study Group 0.12:	Advanced computational methods for recovery of high-resolution gravity field models
Joint Study Group 0.13:	Integral equations of potential theory for continuation and transformation of classical and new gravitational observables
Joint Study Group 0.14:	Fusion of multi-technique satellite geodetic data
Joint Study Group 0.15:	Regional geoid/quasi-geoid modelling – Theoretical framework for the sub-centimetre accuracy
Joint Study Group 0.16:	Earth's inner structure from combined geodetic and geophysical sources
Joint Study Group 0.17:	Multi-GNSS theory and algorithms
Joint Study Group 0.18:	High resolution harmonic analysis and synthesis of potential fields
Joint Study Group 0.19:	Time series analysis in geodesy
Joint Study Group 0.20:	Space weather and ionosphere
Joint Study Group 0.21:	Geophysical modelling of time variations in deformation and gravity
Joint Study Group 0.22:	Definition of next generation terrestrial reference frames (discontinued in 2017)

Overview

Terms of reference

The Inter-Commission Committee on Theory (ICCT) was formally approved and established after the IUGG XXI Assembly in Sapporo, 2003, to succeed the former IAG Section IV on General Theory and Methodology and, more importantly, to interact actively and directly with other IAG entities, namely commissions, services and the Global Geodetic Observing System. IAG approved the continuation of ICCT at the IUGG XXIII Assembly in Melbourne, 2011. At the IUGG XXIV Assembly in Prague, 2015, ICCT became a permanent entity within the IAG structure. The structure of the ICCT is specified in the IAG by-laws.

The main objectives of the ICCT are:
- to be the international focal point of theoretical geodesy,
- to encourage and initiate activities to further geodetic theory,
- and to monitor research developments in geodetic modelling.

ICCT's Steering Committee 2015-2019

President	*Pavel Novák* (Czech Republic)
Vice-President	*Mattia Crespi* (Italy)
Past-President	*Nico Sneeuw* (Germany)
Commission 1	*Geoffrey Blewitt* (USA)
Commission 2	*Roland Pail* (Germany)
Commission 3	*Manabu Hashimoto* (Japan)
Commission 4	*Marcelo Santos* (Canada)
GGOS	*Hansjörg Kutterer* (Germany)
IGFS	*Riccardo Barzaghi* (Italy)
IERS	*Jürgen Müller* (Germany)

During the 2015-2019 period, the ICCT Steering Committee met during regular meetings of the IAG's Executive Committee as their memberships largely overlap. The ICCT President informed members of the two committees about the structure of the ICCT, activities of its joint study groups and about organization of the IX Hotine-Marussi Symposium on Mathematical Geodesy organized by ICCT in 2018, see below. The next (and last) meeting of the committee will be organized during the General Assembly of IAG and IUGG, Montreal, Canada, in July 2019.

Website

The ICCT website is hosted at http://icct.kma.zcu.cz by the web server of the Department of Geomatics, University of West Bohemia in Pilsen, and is powered by the MediaWiki Engine (similar to that used for the Wikipedia, a free, web-based multilingual encyclopaedia project). Due to this setup, the content of the ICCT Website can easily be edited by any authorized personnel (members of the ICCT Steering Committee and Chairs of the Study Groups). Thus, the website could be used by for fast and easy communication of ideas among the members of the Study Groups.

IX Hotine-Marussi Symposium

The IX Hotine-Marussi Symposium on Mathematical Geodesy was held from 18 to 22 June 2018. The symposium took place at the Faculty of Civil and Industrial Engineering of the Sapienza University of Rome, Italy, in the ancient Chiostro of the Basilica of S. Pietro in Vincoli.

The symposium was attended by 119 participants from 30 countries who contributed 120 papers (83 oral presentations and 37 posters). The scientific program of the symposium was organized in 10 sessions that were mainly modelled thematically after the ICCT study group topics and mostly convened by their chairs:

1. Geodetic methods in Earth system science (N. Sneeuw)
2. Theory of multi-GNSS parameter estimation (A. Khodabandeh, M. Crespi)
3. Digital terrain modelling (R. Barzaghi)
4. Space weather and atmospheric modelling (K. Börger, M. Schmidt)
5. Global gravity field modelling and heights systems (D. Tsoulis, S. Claessens)
6. Theory of modern geodetic reference frames and Earth's rotation (Z. Altamimi)
7. Deformation and gravity field modelling at regional scales (J. Huang, Y. Tanaka)
8. Estimation theory and inverse problems in geodesy (A. Dermanis)
9. Advanced numerical methods in geodesy (R. Čunderlík)
10. Multi-sensor and time series data analysis (W. Kosek, K. Sosnica)

Additionally, a special session at the Accademia dei Lincei (the oldest scientific academy in the world, established in 1603 by Federico Cesi) was held on 19 June 2018. Its program consisted of 6 invited talks focused on interactions of geodesy and

- oceanography (M. H. Rio)
- glaciology (O. Francis, T. van Dam)
- atmosphere (R. Pacione, J. Douša)
- mathematics (W. Freeden, F. Sansò)
- solid Earth system structure from space (R. Haagmans)
- seismology (A. Peresan, M. Crespi, A. Mazzoni, G. Panza)

The special session was organized by Fernando Sansò, Emeritus at the Politecnico di Milano, member of the Accademia dei Lincei and long-term driving force behind the Hotine-Marussi symposia series.

The scientific program of the symposium was complemented with a social program including a night tour of the Vatican Museum and the Sistine Chapel.

The IX Hotine-Marussi Symposium was successful also due to the effort and organization skills of the local organizing committee chaired by Mattia Crespi (Rome), the vice-president of ICCT. The Hotine-Marussi symposium has been hosted by the Sapienza University of Rome already for the third time in a row. For more information on the IX Hotine-Marussi Symposium, please visit https://sites.google.com/uniroma1.it/hotinemarussi2018.

Participants of the IX Hotine-Marussi Symposium, 18-22 June 2018, in the Chiostro of the Basilica of S. Pietro in Vincoli, Rome, Italy.

Further Meetings

The Hotine-Marussi Symposium is not the only scientific meeting with the visible presence of the ICCT. Sessions dedicated to recent general developments in geodetic theory were organized by ICCT-related personnel at the EGU General Assemblies 2016-2019 in Vienna. Other sessions on selected particular topics of theoretical geodesy related to joint study groups' activities were also organized at IAG's commissions meetings. Other meetings and/or session are listed within reports of individual joint study groups in the following text.

Summary on activities of study groups

The activities of the ICCT are related namely to research activities carried out by members of its joint study groups. Their final reports specify main research areas under investigation, achieved results and outputs (namely publications and presentations). Based on the content of the submitted reports, it can be concluded that the joint study groups have been active, although the level of co-operation and/or interaction between its members is not necessarily the same for all the joint study groups. The reports were (with few exceptions) standardized based on instruction concerning the length, structure and level of detail.

Most importantly, all chairmen delivered their reports in time which confirmed the main idea behind the current ICCT structure: involving young enthusiastic researchers as study group chairmen who actively cooperate internationally with research topics which matter to current geodesy. All study groups but one stayed active for the entire period 2015-2019. Moreover, new topics were identified (implications of new digital terrain models and namely of new instrumentation on geodetic theory) for future joint study groups within the ICCT structure 2019-2023.

Joint Study Group 0.10: High-rate GNSS

Chair: *Mattia Crespi (Italy)*
Affiliation: *Commissions 1, 3, 4 and GGOS*

Members

Juan Carlos Baez (Chile)
Elisa Benedetti (United Kingdom)
Geo Boffi (Switzerland)
Gabriele Colosimo (Switzerland)
Athanasios Dermanis (Greece)
Roberto Devoti (Italy)
Jeff Freymueller (USA)
Joao Francisco Galera Monico (Brazil)
Jianghui Geng (Germany)
Kosuke Heki (Japan)
Melvin Hoyer (Venezuela)
Augusto Mazzoni (Italy)
Nanthi Nadarajah (Australia)
Yusaku Ohta (Japan)
Ruey-Juin Rau (Taiwan)
Eugenio Realini (Italy)
Chris Rizos (Australia)
Giorgio Savastano (USA)
Nico Sneeuw (Germany)
Peiliang Xu (Japan)

1. Activities

1.1 Summary

Since the very beginning of the GNSS era, the goal has been pursued to widen as much as possible the range in space (from local to global) and time (from short to long term) of the observed phenomena, in order to cover the largest possible field of applications, both in science and in engineering.

Obviously, two complementary, but primary as well, goals were to get this information with the highest accuracy and in the shortest time: they are the key goals pursued by high-rate GNSS. Starting from the noble birth in seismology, and the very first experiences in structural monitoring, high-rate GNSS had already demonstrated its usefulness and power in providing precise positioning information in fast time-varying environments.

Nevertheless, the contemporary technological evolution both impacting GNSS and other IoT (Internet of Things) sensors able to provide kinematic parameters, thus a continuously increasing heap of data, asked for due attention, in order both to define the approaches for the optimal data processing and integration, and to assess the actually achievable accuracies in different applications.

Exactly these objectives were pursued during the activities of this JSG, covering a variety of applications: monitoring of ground shaking and displacement during earthquakes and tracking the fast variations of the ionosphere, also for contribution to tsunami early warning; real-time controlling landslides and the safety of structures; providing detailed trajectories and kinematic parameters (not only position, but also velocity and acceleration) of (high) dynamic platforms such as airborne sensors, high-speed terrestrial vehicles, athlete and sport vehicles, and even pedestrians and human gesture.

1.2 Research

GNSS seismology, ionospheric seismology

- ground shaking, seismic waveforms and coseismic displacements: [5, 8, 16, 17, 18, 19, 20, 21, 22, 24, 26, 29, 30, 32, 44, 54, 56, 61, 72 and 73]
- seismic inversion, focal mechanism, magnitude estimation: [2, 25, 34, 36, 37, 52, 58, 62 and 63]
- tsunami early warning: [4, 35, 46, 53 and 60]
- Earthquake early warning: [23, 38, 39, 40, 41, 42 and 43]
- sensors, infrastructures and databases: [1, 3, 9 and 10].

Integration of GNSS with other sensors

- IoT sensors integration [6, 7, 27, 28, 33, 55, 57, 59, 64 and 71].

Navigation

- methodology [49, 50, 51 and 70]
- kinematic estimation of position and velocity [11, 12, 13, 14, 15, 31, 45, 47, 48, 65, 66, 67, 68 and 69].

1.3 Sessions organization at international congresses/symposia/workshops

- Organization of the session *Theory of multi-GNSS parameter estimation (A. Khodabandeh, M. Crespi)* at the *IX Hotine-Marussi Symposium* (Rome, Italy) in 2018.
- Co-organization of the sessions *High-precision GNSS: methods, open problems and Geoscience applications* at the European Geoscience Union General Assembly (Vienna, Austria) in 2017, 2018 and 2019.

1.4 Editorial activity

- Special Issue of Advances in Space Research on *High-rate GNSS: Theory, Methods, and Engineering/Geophysical Applications* 59(11): 2689-2830; Editor: Peiliang X; see http://www.sciencedirect.com/science/journal/02731177/59/11.
- Special Feature of Measurement Science and Technology on *High-Precision Multi-Constellation GNSS: Methods, Selected Applications and Challenges* (Eds: Paziewski J, Crespi M, see https://iopscience.iop.org/journal/0957-0233/page/High-Precision-Multi-Constellation-GNSS)
- Special Issue of Remote Sensing on *High-precision GNSS: Methods, Open Problems and Geoscience Applications* (Eds: Li X, Paziewski J, Crespi M, see https://www.mdpi.com/journal/remotesensing/special_issues/GNSS_rs)

1.5 Technology transfer and relevant applications in science and engineering

- VADASE algorithm implemented by Leica in the firmware of GR series GNSS receiver since 2 September 2015 (http://blog.leica-geosystems.com/leica-vadase-is-worlds-first-autonomous-gnss-monitoring-solution-onboard-a-stand-alone-receiver)
- VARION algorithm under incorporation into JPL’s Global Differential GPS System as a novel contribution to future integrated operational tsunami early warning systems (https://www.nasa.gov/feature/jpl/scientists-look-to-skies-to-improve-tsunami-detection)

2. Cooperation/Interactions with IAG Commissions and GGOS

Commission 3

- SC 3.5: Tectonics and Earthquake Geodesy – Chair: *Haluk Ozener* (Turkey)

Commission 4

- SC 4.1: Emerging Positioning Technologies and GNSS Augmentation – Chair: *Vassilis Gikas* (Greece)
- SC 4.2: Geo-spatial Mapping and Geodetic Engineering – Chair: *Jinling Wang* (Australia)
- SC 4.3: Atmosphere Remote Sensing – Chair: *Michael Schmidt* (Germany)
- SC 4.4: Multi-constellation GNSS – Chair: *Pawel Wielgosz* (Poland)

GGOS

- Geohazards Monitoring Focus Area – Chair: *John LaBrecque* (USA)

Report: Global Navigation Satellite System to Enhance Tsunami Early Warning Systems (Editors: John LaBrecque, John Rundle, Gerald Bawden), see http://www.ggos.org/media/filer_public/64/36/6436cc04-00cf-407a-a365e79ce26378f2/gtews2017.pdf

3. Future prospects

3.1 Research

High-rate GNSS general problems

- Full GNSS multi-constellations integration for real-time solutions (functional and stochastic models).
- Accuracy assessment and stochastic modeling of very high rate (low-cost) multi-frequency multi-constellation GNSS receivers.
- Optimal models for real-time monitoring of GNSS permanent stations measurements noise and clocks.

GNSS seismology, structural monitoring

- Optimal statistical testing for reliable real-time detection of significant velocities/displacements.

Ionospheric seismology

- Optimal filtering for real-time ionospheric disturbance detection.
- GEO/MEO GNSS satellites integration, also with LEO occultation satellites.
- Further investigations on ionospheric total electron content variations prior to major earthquakes.

Sensors integration

- Functional and stochastic modeling of low-cost dual frequency GNSS receivers and newest IoT sensors for enhanced kinematic solutions.

3.2 Sessions organization at international congresses/symposia/workshops

- Organization of a session on high-rate GNSS at the *X Hotine-Marussi Symposium* in 2022.
- Co-organization of the session *High-precision GNSS: methods, open problems and Geoscience applications* at next European Geoscience Union General Assemblies.

3.3 Editorial activity

- Special Issues on peer-review journals on high-rate GNSS.
- JSG publications: proposal for two (one science and the other engineering oriented) state-of-the-art review papers on high-rate GNSS co-authored by the JSG members.

3.4 Technology transfer and relevant applications in science and engineering

- Reference bibliography in high-rate GNSS.
- Questionnaire within the Members of the JSG for starting an inventory of methodologies, technologies and applications in high-rate GNSS.

4. Publications

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3. Báez JC, Leyton F, Troncoso C, Del Campo F, Bevis M, Vigny C, Moreno M, Simons M, Kendrick E, Parra H, Blume F (2018) The Chilean GNSS network: Current status and progress toward early warning applications. *Seismological Research Letters* 89(4): 1546-1554

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5. Fratarcangeli F, Ravanelli M, Mazzoni A, Colosimo G, Benedetti E, Branzanti M, Savastano G, Verkhoglyadova O, Komjathy A, Crespi M (2018) The variometric approach to real-time high-frequency geodesy. *Rendiconti Lincei* 29: 95-108

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28. Shu Y, Fang R, Geng J, Zhao Q, Liu J (2018) Broadband velocities and displacements from integrated GPS and accelerometer data for high-rate seismogeodesy. *Geophysical Research Letters* 45(17): 8939-8948
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Joint Study Group 0.11: Multiresolutional aspects of potential field theory

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1. Activities

1.1 Summary

Potential field theory defines the theoretical backbone of gravity field modelling and interpretation. The mathematical description and numerical computation of the gravity signal of finite distributions enters a series of applications from terrain effects and geoid computations over finite geographical regions to reduction and downward continuation of global satellite data. The study of the field induced by ideal geometrical bodies, such as the cylinder, the rectangular prism or the generally shaped polyhedron expresses the formal aspect of this bundle of activities and are linked to local or regional datasets. At the same time integral expressions and theorems of potential theory as well as the utilization of spectral tools permit the incorporation of global data, such as digital terrain or crustal databases and the realization of the corresponding global solutions.

The development, numerical implementation and validation of analytical, numerical, spectral, hybrid and multiresolutional tools for the evaluation of the different potential field quantities in the view of and related to the currently available global terrain and density information as well as satellite data, especially direct observations of second order derivatives of the potential, was the core motivation and key objective behind the activities of JSG 0.11. The considered research topics were pursued both in the context of forward and inverse potential field modelling.

The performed activities covered a wide range of applications including the gravity signal of ideal sources, in particular polyhedrons and spherical prisms, global topographic reduction and Bouguer maps, geoid, third-order gravitational tensor, spectral gravity forward modelling, mass transport, inverse gravimetric problem and approximation methods.

1.2 Research

Gravity signal of ideal sources

- Polyhedral gravity signal (D'Urso 2015, D'Urso and Trotta 2017).
- Spherical prismatic gravity signal (Roussel et al. 2015).

Global terrain and crustal data

- Spherical harmonic analysis of global crustal database CRUST 1.0, related gravity field signal and Moho signature implications (Tenzer et al. 2015).
- Global gravimetric terrain corrections at 3-arcsec spatial resolution (Hirt et al. 2019).
- Topographic potential and its derivatives compared with numerical integration (Hirt et al. 2016, Kuhn and Hirt 2016).

Potential satellite data

- Processing and interpolation of GOCE gradiometric data for the production of gradient grids (Bouman et al. 2016, Tsoulis and Moukoulis 2019).

Integral expressions

- Third-order gradients of the potential using integral formulas (Šprlák and Novák 2015).
- Integral transforms for potential and gradients in the frame of boundary value problems (Novák et al. 2017).

Spectral techniques

- Spectral gravity forward modelling, methodological aspects and convergence issues (Root et al. 2016, Bucha et al. 2019a, b).
- Gravity anomalies (Tenzer et al. 2019) and geoid computations (Tenzer et al. 2015, Tenzer et al. 2016, Foroughi et al. 2019).
- Third-order gradients of the potential using spherical harmonic synthesis (Hamáčková et al. 2016).

Mass transport and regional forward modelling

- Glacier and ice sheet mass variations using GRACE data (Harig and Simons 2015, 2016, Beveridge et al. 2018, Bevis et al. 2019).
- Glacial isostatic adjustment using the observed gravity field to enhance geophysical models (Root et al. 2015).

Inverse modelling

- Separation of gravity and magnetic data and inversion for the determination of 3D hidden crustal structures (Michel 2015a, Prutkin et al. 2017), planetary magnetic field determination by inversion and downward continuation taking into account regional characteristics of data (Plattner and Simons 2015), inversion of electric and magnetic data for an object with spherical symmetry (Leweke et al. 2018a), theory of inverse gravimetric and inverse magnetic problems as ill-posed problems with emphasis on the Earth (Michel and Orzlowski 2016, Leweke et al. 2018b).
- Inversion of satellite gravity data for source depth determination by means of Slepian functions (Galanti et al. 2019), guideline methodology for the utilization of Slepian functions for inverse problems with regional data (Michel and Simons 2017).
- Inversion of potential fields sampled in terms of vector observations at satellite altitude using gradient vector Slepian functions as local base functions (Plattner and Simons 2015, 2017), spherical signal estimation and spectral analysis (Simons and Plattner 2015).
- Matching pursuit-type greedy algorithms for linear inverse problem solving (Michel 2015b, Kontak and Michel 2018a) and for the non-linear inverse gravimetric problem, i.e., given a gravity field, determine the surface of the gravitating object (Kontak and Michel 2018b), regularization parameters and convergence in matching pursuit algorithms

(Gutting et al. 2017, Michel and Orzlowski 2017), decrease of iterations by introducing an orthogonal projection step, leading to better gravity modelling and downward continuation results (Michel and Telschow 2016).

Estimation and approximation methods

- Trial functions for approximation on the sphere (Freeden et al. 2018), techniques and quality measures for uniform distributions of points on the sphere (Ishtiaq and Michel 2017, Ishtiaq et al. 2019), spatially concentrated and spectrally band-limited vector trial functions (Slepian functions) on the sphere (Leweke et al. 2018c).
- Using a learning algorithm for the construction of an optimal basis for gravity field modelling out of spherical harmonics and radial basis functions (Michel and Schneider 2019), a sparse estimate of a probability density on the sphere applying a greedy algorithm (Gramsch et al. 2018).
- Spin-weighted or generalized spherical harmonics and their geodetic applications (Michel and Seibert 2018).

1.3 Sessions organization at international congresses/symposia/workshops

- Organization of Session G1.3 *Analytical, numerical and multiresolutional techniques for forward modelling of gravitational fields of mass distributions (D. Tsoulis, M. Sideris, P. Novák, V. Michel)* at the European Geoscience Union General Assembly (Vienna, Austria) in 2017.
- Organization of Session *global gravity field modelling and height systems (D. Tsoulis, S. Claessens)* at the *IX Hotine-Marussi Symposium* (Rome, Italy) in 2018.
- Organization of Inter-Association Symposium *JG02 Theory and methods of potential fields (IAG, IAGA; D. Tsoulis, S. Claessens, M. Fedi)* at the 27th IUGG General Assembly (Montreal, Canada) in 2019.

2. Future prospects

2.1 Research

All considered research topics define open scientific areas with numerous open questions emerging from the efficient and accurate numerical implementation of the individual theoretical developments and the utilization of current and upcoming terrestrial and satellite global datasets. An indicative list of themes for further consideration would include:

Forward modelling

- Numerical evaluation and validation of third order potential derivatives with an attempt to evaluate them alternatively (analytically or numerically) over bounded regions.
- Thorough review, numerical implementation and comparison of different available forward modelling algorithms.
- Spectral and multiresolutional computations of the potential function and its derivatives for known distributions and comparisons with available numerical and analytical solutions.

Inverse modelling

- Inclusion in existing and evolving inverse problem solving algorithms of high and very high degree gravity field models to represent the observed gravity signal.
- Validation of inverse algorithms by incorporating accurate geometric modelling of the hidden sources and exact computation of their gravity signal in the frame of closed loop simulations with the available forward modelling methods.

2.2 Sessions organization at international congresses/symposia/workshops

- Organization of a session on theory and methods of potential fields at the *X Hotine-Marussi Symposium* in 2022.
- Co-organization of a session on theory and methods of potential fields at the next European Geoscience Union General Assembly.

2.3 Editorial activity

- Special Issues on peer-review journals on potential fields.
- JSG publications: proposal for several state-of-the-art review papers on potential fields co-authored by the JSG members.

3. Publications

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5. Bucha B, Hirt C, Kuhn M (2019b) Divergence-free spherical harmonic gravity field modelling based on the Runge–Krarup theorem: a case study for the Moon. *Journal of Geodesy* 93(4): 489-513

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12. Gutting M, Kretz B, Michel V, Telschow R (2017) Study on parameter choice methods for the RFMP with respect to downward continuation, *Frontiers in Applied Mathematics and Statistics* 3, article 10; doi: 10.3389/fams.2017.00010.
13. Hamáčková E, Šprlák M, Pitoňák M, Novák P (2016) Non-singular expressions for the spherical harmonic synthesis of gravitational curvatures in a local north-oriented reference frame. *Computers and Geosciences* 88: 152-162
14. Harig C, Simons FJ (2015) Accelerated West Antarctic ice mass loss continues to outpace East Antarctic gains. *Earth and Planetary Science Letters*, 8+7 pp.
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27. Michel V (2015a) Tomography – problems and multiscale solutions. *Handbook of Geomathematics (Freeden W, Nashed MZ and Sonar T, eds.), 2nd edition*, Springer, Berlin, Heidelberg, 2087-2119

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30. Michel V, Telschow R (2016) The regularized orthogonal functional matching pursuit for ill-posed inverse problems. *SIAM Journal on Numerical Analysis* 54: 262-287
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32. Michel V, Seibert K (2018) *A mathematical view on spin-weighted spherical harmonics and their applications in geodesy, Handbuch der Geodäsie (Freeden W, Rummel R, eds.)*, Springer Reference Naturwissenschaften, Springer Spektrum, Berlin, Heidelberg, 113 pp.
33. Michel V, Simons FJ (2017) A general approach to regularizing inverse problems with regional data using Slepian wavelets. *Inverse Problems* 33: 125016, 28 pp.
34. Michel V, Schneider N (2019) A first approach to learning a best basis for gravity field modelling. *Siegen Preprints on Geomathematics*, preprint SPG 21.
35. Novák P, Šprlák M, Tenzer R, Pitoňák M (2017) Integral formulas for transformation of potential field parameters in geosciences. *Earth-Science Reviews* 164(1): 208-231
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39. Prutkin Y, Bleibinhaus F, Jahr T, Vajda P, Novák P, Tenzer R (2017) Interpretation of gravity and magnetic data with geological constraints for 3D structure of the Thuringian Basin, Germany. *Journal of Applied Geophysics* 136(1): 35-41
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47. Tenzer R, Hirt C, Claessens S, Novák P, Pitoňák M, Šprlák M (2016) Contribution of mass density heterogeneities to the quasigeoid-to-geoid separation. *Journal of Geodesy* 90(1): 65-80
48. Tenzer R, Foroughi I, Hirt C, Novák P, Pitoňák M (2019) How to calculate Bouguer gravity data in planetary studies. *Surveys in Geophysics* 40(1): 107-132
49. Tsoulis D, Moukoulis C (2019) Processing aspects of level 2 GOCE gradiometer data for regional applications. *Geophysical Journal International* 216 (2): 1116-1131

Joint Study Group 0.12: Advanced computational methods for recovery of high-resolution gravity field models

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1. Activities

1.1 Research

Activities of the JSG-0.12 during the whole period 2015−2019 have been mainly focused on further development of the advanced computational methods for recovery of high-resolution gravity field models. The numerical approaches based on (i) the discretization methods like the boundary element method (BEM), finite element method (FEM) and finite volume method (FVM), or on (ii) meshless methods like the method of fundamental solution (MFS) and singular boundary method (SBM), or on (iii) others weak solution concepts, have been used:

- to solve numerically the geodetic boundary-value problems (GBVPs), see e.g., (*Čunderlík 2016b*), (*Čunderlík et al. 2016a,b, 2018*), (*Holota 2018*), (*Holota and Nesvadba 2019a,b*), (*Macák et al. 2016*) and (*Medľa et al. 2018*),
- to process the GOCE satellite measurements, see (*Čunderlík 2016*),
- to develop nonlinear diffusion filtering of various geodetic data, see, e.g., (*Kollár et al. 2016*) and (*Čunderlík et al. 2016*).

To solve such problems in spatial domains while obtaining high-resolution numerical solutions, such approaches require parallel implementations and large-scale parallel computations on clusters with distributed memory using the MPI (Message Passing Interface). In the following the main activities are briefly described.

In case of FVM approach, an iterative approach to solve the nonlinear satellite-fixed GBVP has been developed. In this approach an unknown direction of the actual gravity vector together with the disturbing potential is updated in every iteration (*Macák et al. 2016*). An original method to treat the oblique derivative problem using an up-wind based FVM has been proposed. Namely, the second order up-wind numerical scheme has been derived for non-uniform grids above the real Earth’s topography (*Medľa and Mikula 2016*). Such an approach has involved a construction of the non-uniform hexahedron 3D grids above the Earth's surface that is based on an evolution of a surface, which approximates the Earth's topography, by its mean curvature. To obtain optimal shapes of non-uniform 3D grid, the proposed evolution has been accompanied by a tangential redistribution of grid nodes. Afterwards, the Laplace equation has been discretized using the FVM developed for such a non-uniform grid. The oblique derivative boundary condition has been treated as a stationary advection equation resulting to a new up-wind type discretization suitable for non-uniform 3D grids (*Medľa et al. 2018*).

To reduce a numerical complexity of the boundary integral approaches, e.g., the direct BEM with collocation or MFS and SBM as meshless methods, we have focused on elimination of the far zones interactions using the Hierarchical matrices (H-matrices). To compress the "far field parts" of the system matrices, the Adaptive Cross Approximation (ACA) algorithm have been implemented. It is based on the idea that numerically rank-deficient sub-blocks, which correspond to interactions of well-separated groups, can be efficiently compressed through an approach very similar to the column-pivoted LU decomposition. The first experiments show that the ACA algorithm effectively reduces memory requirements and computational costs while giving practically the same results. It means that implementations of the H-matrices as a compression technique allow to increase a level of the discretization considerably w.r.t. available memory of the accessible HPC facilities. This is promising for further development of the boundary integral approaches for high-resolution gravity field modelling.

In case of nonlinear diffusion filtering, the existing method based on the regularized Perona-Malik model has been extended in order to avoid undesirable smoothing of local extremes. This has been treated by a modification of the diffusivity coefficient, which now depends on a combination of the edge detector and a mean curvature of the filtered function. A semi-implicit numerical scheme has been derived for this approach (*Kollár et al. 2016*), which is based on a numerical solution of partial differential equations on closed surfaces using the surface FVM. Sensitivity parameters of the proposed "edge and extremes detector" have been experimentally tuned for different types of filtered data (*Čunderlík et al. 2016*). The similar semi-implicit numerical scheme has been also derived for data given on 2D rectangular grids.

The achieved results of all activities have been published in several papers (see below) and they were presented at the major geodetic conferences, e.g. at the *EGU General Assemblies* in Wien (every year), during the Joint Commission 2 and IGFS Meetings – *GGHS-2016* (Thessaloniki, Greece, 2016) and *GGHS-2018* (Copenhagen, Danmark, 2018), at the *IAG-IASPEI Scientific Assembly* (Kobe, Japan, 2017) or at the *IX Hotine-Marussi Symposium* (Rome, Italy, 2018).

1.2 Sessions organization at international congresses/symposia/workshops:

- Organization of the session *Advanced numerical methods in geodesy (R. Čunderlík)* at the *IX Hotine-Marussi Symposium* (Rome, Italy) in 2018.
- Co-organization of the sessions *Recent Developments in Geodetic Theory (P. Holota, N. Sneeuw, B. Heck, R. Čunderlík, O. Nesvadba)* at the European Geoscience Union General Assemblies (Wien, Austria) in 2016, 2017, 2018 and 2019.

2. Publications:

1. Čunderlík R (2016) Precise modelling of the static gravity field from GOCE second radial derivatives of the disturbing potential using the method of fundamental solutions. *IAG Symposia Series* 144: 71-81
2. Čunderlík R, Kollár M, Mikula K (2016) Filters for geodesy data based on linear and nonlinear diffusion. *International Journal on Geomathematics* 7(2): 239-274
3. Čunderlík R, Macák M, Medľa M, Mikula K, Minarechová Z (2018a) Numerical methods for solving the oblique derivative boundary value problems in geodesy. In: Freeden W, Rummel R (eds.) *Handbuch der Geodäsie*. Springer Reference Naturwissenschaften. Springer Spektrum, Berlin, Heidelberg, pp.1-48; doi: 10.1007/978-3-662-46900-2_105-1.

4. Čunderlík R, Mikula K, Minarechová Z, Macák M (2018b) Computational methods for high-resolution gravity field modeling. In: Grafarend E (eds) *Encyclopedia of Geodesy*. Encyclopedia of Earth Sciences Series. Springer, Cham.
5. Holota P (2018) Domain transformation and the iteration solution of the linear gravimetric boundary value problem. *IAG Symposia Series* 147: 47-52
6. Holota P, Nesvadba O (2019a) Galerkin's matrix for Neumann's problem in the exterior of an oblate ellipsoid of revolution: gravity potential approximation by buried masses. *Studia Geophysica et Geodaetica* 63(1): 1-34
7. Holota P, Nesvadba O (2019b) Boundary complexity and kernel functions in classical and variational concepts of solving geodetic boundary value problems. *IAG Symposia Series* 149: 31-41
8. Kollár M, Čunderlík R, Mikula K (2016) Nonlinear diffusion filtering influenced by mean curvature. In: ALGORITMY-2016 – 20th Conference on Scientific Computing. Proceedings of contributed papers, ISBN: 978-80-227-4544-4, pp. 33-43.
9. Macák M, Mikula K, Minarechová Z, Čunderlík R (2016) On an iterative approach to solving the nonlinear satellite-fixed geodetic boundary-value problem. *IAG Symposia Series* 142: 185-191
10. Medľa M, Mikula K (2016) New second order up-wind scheme for oblique derivative boundary value problem. In: ALGORITMY-2016 – 20th Conference on Scientific Computing, Proceedings of contributed papers, ISBN: 978-80-227-4544-4, pp. 254-263.
11. Medľa M, Mikula K, Čunderlík R, Macák M (2018) Numerical solution to the oblique derivative boundary value problem on non-uniform grids above the Earth topography. *Journal of Geodesy* 92: 1-19
12. Nesvadba O, Holota P (2016) An ellipsoidal analogue to Hotine's kernel: accuracy and applicability. *IAG Symposia Series* 144: 93-100
13. Nesvadba O, Holota P (2016) An OpenCL implementation of ellipsoidal harmonics. *IAG Symposia Seriers* 142: 195-203
14. Roese-Koerner L, Schuh WD (2016) Effects of different objective functions in inequality constrained and rank-deficient least-squares problems. *IAG Symposia Series* 142: 325-331

Joint Study Group 0.13: Integral equations of potential theory for continuation and transformation of classical and new gravitational observables

Chair:	*Michal Šprlák (Australia)*
Affiliation:	*Commission 2 and GGOS*

Members

Alireza Ardalan (Iran)
Mehdi Eshagh (Sweden)
Will Featherstone (Australia)
Ismael Foroughi (Canada)
Petr Holota (Czech Republic)
Juraj Janák (Slovakia)
Otakar Nesvadba (Czech Republic)
Pavel Novák (Czech Republic)
Martin Pitoňák (Czech Republic)
Robert Tenzer (China)
Guyla Tóth (Hungary)

1. Activities

1.1 Summary

The description of the Earth's gravitational field and its temporal variations belongs to the fundamental pillars of modern geodesy. Various observational techniques for collecting gravitational data have been invented based on terrestrial, marine, airborne and more recently, satellite sensors. Different parametrization methods of the gravitational field were established in geodesy, including those based on solving boundary/initial value problems of potential theory, through Fredholm's integral equations.

Traditionally, Stokes's, Vening-Meinesz's and Hotine's integrals have been of main interest as they accommodated geodetic applications in the past. In recent history, new geodetic integral transformations were formulated as new gravitational observables became gradually available with the advent of precise GNSS (Global Navigation Satellite Systems) positioning, satellite altimetry and aerial gravimetry/gradiometry. The family of integral transformations has enormously been extended with satellite-to-satellite tracking and satellite gradiometric data available from recent gravity-dedicated satellite missions.

This study group aims at systematic treatment of geodetic integral transformations. Many solutions are based on spherical approximation that cannot be justified for globally distributed satellite data and with respect to requirements of various data users requiring gravitational data to be distributed at the reference ellipsoid or at constant geodetic altitude. On the other hand, the integral equations in spherical approximation possess symmetric properties and also motivate for adopting a generalized notation. New numerically efficient, stable and accurate methods for upward/downward continuation, comparison, validation, transformation, combination and/or for interpretation of gravitational data are also of high interest with increasing availability of large amounts of new data.

1.2 Research

Spherical integral transformations

- Geoid determination (Afrasteh et al. 2018, Foroughi et al. 2017, 2018, 2019, Goli et al. 2018b, Janák et al. 2017, Sheng et al. 2018)
- New integral transformations and their mathematical properties
  - Satellite-to-satellite tracking observables (Eshagh and Šprlák 2016, Šprlák and Eshagh 2016)
  - 2nd order gravitational tensor components (Romeshkani and Eshagh 2015, Šprlák and Novák 2017, Šprlák et al. 2015)
  - 3rd order gravitational tensor components (Šprlák and Novák 2015, 2016, 2017, 2018).
- Spectral combination of 3rd order gravitational tensor components (Pitoňák et al. 2018).
- Geophysical applications
  - Forward modelling (Tenzer et al. 2017b, Šprlák et al. 2018, Yang et al. 2018)
  - Estimation of volumetric density (Ye et al. 2018)
  - Determination of Moho, elastic thickness and sub-crustal stress (Eshagh 2015, 2016a, 2016b, 2017, Eshagh and Hussain 2015, 2016, Eshagh and Pitoňák 2019, Eshagh and Romeshkani 2015, Eshagh and Tenzer 2015, Eshagh et al. 2016a, 2016b, 2017, 2018a, 2018b, 2019, Šprlák and Eshagh 2016, Tenzer and Eshagh 2015, Tenzer et al. 2015, 2017a).
- Systematic classification and overview of integral transformations (Novák et al. 2017).

Boundary value problems

- Approximations of the linear boundary value problem (Holota 2016).
- Solution of the spherical curvature boundary value problem (Šprlák and Novák 2016, 2018, Šprlák et al. 2016).
- Solution of the spheroidal Neumann boundary value problem (Holota 2015, Holota and Nesvadba 2018, 2019, Nesvadba and Holota 2016, Šprlák and Tangdamrongsub 2018).
- Solution of the spheroidal horizontal boundary value problem (Šprlák and Tangdamrongsub 2018).

Numerical solutions and formulations of inverse problems:

- Inversion of gravity anomalies for geoid determination (Goli et al. 2018a).
- Inversion of satellite-to-satellite tracking observables, 2nd or 3rd order gravitational tensor components (Eshagh 2017, Eshagh and Pitoňák 2019, Eshagh and Romeshkani 2015, Eshagh and Šprlák 2016, Eshagh et al. 2018a, 2019, Pitoňák et al. 2016, 2017a, 2017b, 2019, Šprlák and Eshagh 2016).
- Inversion of satellite-to-satellite tracking observables and 2nd tensor components in spheroidal approximation (Novák and Šprlák 2018).

1.3 Sessions organization at international congresses/symposia/workshops

- Scientific committee of the IX Hotine-Marussi Symposium, Rome, Italy, 18-22 June 2018 (P. Novák, M. Šprlák, R. Tenzer).
- Session G1.1 on Recent Developments in Geodetic Theory, European Geosciences Union General Assembly 2017 (EGU2017), Vienna, Austria, 23-28 April 2017 (P. Holota, O. Nesvadba).
- Session G1.1 on Recent Developments in Geodetic Theory, European Geosciences Union General Assembly 2018 (EGU2018), Vienna, Austria, 8-13 April 2018 (P. Holota, O. Nesvadba).

- Session G1.1 on Recent Developments in Geodetic Theory, European Geosciences Union General Assembly 2019 (EGU2019), Vienna, Austria, 7-12 April 2019 (P. Holota, O. Nesvadba).

1.4 Editorial activity

- Proceedings of the IX Hotine-Marussi Symposium, Italy, 18-22 June 2018, IAG Symposia Series, Springer (Editor: P. Novák).
- On Significant Applications of Geophysical Methods, Proceedings of the 1st Springer Conference of the Arabian Journal of Geosciences (CAJG-1), Tunisia 2018, (Editor: M. Eshagh).

2. Cooperation/Interactions with IAG Commissions and GGOS

- Commission 2: Working Group 2.2.2 "1 cm geoid experiment", Chair: Y.M. Wang (USA)
- GGOS: Focus Area "Unified Height System", Chair: L. Sánchez (Germany)

3. Future prospects

3.1 Research

Integral transformations:
- Propagation of random and systematic errors through spherical integral transformations
- Efficient and accurate numerical evaluation and effects of the distant zones for spherical integral transformations.
- Extension and overview of the spheroidal integral transformations for oblate planetary bodies.

Boundary value problems:
- Formulation and solution of the spheroidal gradiometric and spheroidal curvature boundary value problems.

Solution of inverse problems:
- Optimal combination of various observations (terrestrial, airborne, satellite) for an accurate gravitational field determination.

3.2 Technology transfer and relevant applications in science and engineering

- Reference bibliography on geodetic integral transformations.

4. Publications

1. Afrasteh Y, Safari A, Sheng MB, Kingdon R, Foroughi I (2018) The effect of noise on geoid height in Stokes-Helmert method. *IAG Symposia Series* 148: 25-29, Springer, Cham; doi: 10.1007/1345_2017_25.
2. Eshagh M (2015) On the relation between Moho and sub-crustal stress induced by mantle convection. *Journal of Geophysics and Engineering* 12: 1-11
3. Eshagh M (2016a) Integral approaches to determine sub-crustal stress from terrestrial gravimetric data. *Pure and Applied Geophysics* 173: 805-825
4. Eshagh M (2016b) On Vening-Meinesz-Moritz and flexural theories of isostasy and their comparison over Tibet Plateau. *Journal of Geodetic Science* 6: 139-151
5. Eshagh M (2017) Local recovery of lithospheric stress tensor from GOCE gravitational tensor. *Geophysical Journal International* 209: 317-333

6. Eshagh M, Hussain M (2015) Relationship amongst gravity gradients, deflection of vertical, Moho deflection and the stresses derived by mantle convections-a case study over Indo-Pak and surroundings. *Geodynamics, Research International Bulletin* 3(4): I-XIII
7. Eshagh M, Romeshkani M (2015) Determination of sub-lithospheric stress due to mantle convection using GOCE gradiometric data over Iran. *Journal of Applied Geophysics* 122: 11-17
8. Eshagh M, Tenzer R (2015) Sub-crustal stress determined using gravity and crust structure models. *Computational Geoscience* 19: 115-125
9. Eshagh M, Hussain M (2016) An approach to Moho discontinuity recovery from on-orbit GOCE data with application over Indo-Pak region. *Tectonophysics* 690B: 253-262
10. Eshagh M, Hussain M, Tenzer R, Romeshkani M (2016a) Moho density contrast in central Eurasia from GOCE gravity gradients. *Remote Sensing* 8: 1-18
11. Eshagh M, Hussain M, Tiampo KF (2016b) Towards sub-lithospheric stress determination from seismic Moho, topographic heights and GOCE data. *Journal of Asian Earth Sciences* 169: 1-12
12. Eshagh M, Šprlák M (2016) On the integral inversion of satellite-to-satellite velocity differences for local gravity field recovery: A theoretical study. *Celestial Mechanics and Dynamical Astronomy* 124: 127-144
13. Eshagh M, Ebadi S, Tenzer R (2017) Isostatic GOCE Moho model for Iran. *Journal of Asian Earth Sciences* 138: 12-24
14. Eshagh M, Ashagrie A, Bedada TB (2018a) Regional recovery of gravity anomaly from the inversion of diagonal components of GOCE gravitational tensor: a case study in Ethiopia. *Artificial Satellites* 53: 55-74
15. Eshagh M, Steinberger B, Tenzer R, Tassara A (2018b) Comparison of gravimetric and mantle flow solutions for lithospheric stress modelling and their combination. *Geophysical Journal International* 213: 1013-1028
16. Eshagh M, Pitoňák M (2019) Elastic thickness determination from on-orbit GOCE data and CRUST1.0. *Pure and Applied Geophysics* 176: 685-696
17. Eshagh M, Pitoňák M, Tenzer R (2019) Lithospheric elastic thickness estimates in central Eurasia. *Terrestrial, Atmospheric and Oceanic Sciences Journal* 30: 73-84
18. Foroughi I, Afrasteh Y, Ramouz S, Safari A (2017) Local evaluation of Earth gravitational models, case study: Iran. *Geodesy and Cartography* 43: 1-13
19. Foroughi I, Vaníček P, Novák P, Kingdon RW, Sheng M, Santos MC (2018) Optimal combination of satellite and terrestrial gravity data for regional geoid determination using Stokes-Helmert's method, the Auvergne test case. *IAG Symposia Series* 148: 37-43, Springer, Cham; doi: 10.1007/1345_2017_22.
20. Foroughi I, Vaníček P, Kingdon RW, Goli M, Sheng M, Afrasteh Y, Novák P, Santos M (2019) Sub-centimetre geoid. *Journal of Geodesy* 93(6): 849-868
21. Goli M, Foroughi I, Novák P (2018a) On estimation of stopping criteria for iterative solutions of gravity downward continuation. *Canadian Journal of Earth Sciences* 55: 397-405
22. Goli M, Foroughi I, Novák P (2018b) The effect of the noise, spatial distribution, and interpolation of ground gravity data on uncertainties of estimated geoidal heights. *Studia Geophysica et geodetica* 63: 35-54

23. Holota P (2015) Summation of series and an approximation of Legendre's functions in constructing integral kernels for the exterior of an ellipsoid: application to boundary value problems in physical geodesy. Leibniz Society of Science at Berlin, Scientific Colloquium Geodesy-Mathematic-Physics-Geophysics in honour of Erik W. Grafarend on the occasion of his 75th birthday, Berlin, Germany, February, 13, 2015. In: Leibniz Online, Jahrgang 2015, Nr. 19, 12 pp. Zeitschrift der Leibniz-Sozietät e.V., ISSN 1863-3285; http://leibnizsozietaet.de/wp-content/uploads/2015/06/holota.pdf).
24. Holota P (2016) Domain transformation and the iteration solution of the linear gravimetric boundary value problem. *IAG Symposia Series* 147: 47-52, Springer, Cham; doi: 10.1007/1345_2016_236.
25. Holota P, Nesvadba O (2018) Boundary complexity and kernel functions in classical and variational concepts of solving geodetic boundary value problems. *IAG Symposia Series* 149: 31-41, Springer, Cham; doi: 10.1007/1345_2018_34.
26. Holota P, Nesvadba O (2019) Galerkin's matrix for Neumann's problem in the exterior of an oblate ellipsoid of revolution: gravity potential approximation by buried masses. *Studia Geophysica et Geodaetica* 63: 1-34
27. Janák J, Vaníček P, Foroughi I, Kingdon R, Sheng M, Santos M (2017) Computation of precise geoid model of Auvergne using current UNB Stokes-Helmert's approach. *Contribution to Geodesy and Geophysics* 47: 201-229
28. Nesvadba O, Holota P (2016) An ellipsoidal analogue to Hotine's kernel: accuracy and applicability. *IAG Symposia* Series 144: 93-100; doi: 10.1007/1345_2015_133.
29. Novák P, Šprlák M, Tenzer R, Pitoňák M (2017). Integral formulas for transformation of potential field parameters in geosciences. *Earth-Science Reviews* 164: 208-231
30. Novák P, Šprlák M (2018) Spheroidal integral equations for geodetic inversion of geopotential gradients. *Surveys in Geophysics* 39: 245-270
31. Pitoňák M, Šprlák M, Hamáčková E, Novák P (2016) Regional recovery of the disturbing gravitational potential by inverting satellite gravitational gradients. *Geophysical Journal International* 205: 89-98
32. Pitoňák M, Šprlák M, Novák P, Tenzer R (2017a) Regional gravity field modelling from GOCE observables. *Advances in Space Research* 59: 114-127
33. Pitoňák M, Šprlák M, Tenzer R (2017b) Possibilities of inversion of satellite third-order gravitational tensor onto gravity anomalies: a case study for central Europe. *Geophysical Journal International* 209: 799-812
34. Pitoňák M, Eshagh M, Šprlák M, Tenzer R, Novák P (2018) Spectral combination of spherical gravitational curvature boundary-value problems. *Geophysical Journal International* 214: 773-791
35. Pitoňák M, Šprlák M, Novák P, Tenzer R (2019) Regional gravitational field modelling from GOCE measurements. In: Proceedings of the International Seminar – Satellite Methods in Geodesy and Cadastre, 24 January, 2019, Technical University, Brno, Czech Republic, pp. 60-67 (in Slovak).
36. Romeshkani M, Eshagh M (2015) Deterministically-modified integral estimators of tensor of gravitation. *Boletim de Ciências Geodésicas* 21: 189-212
37. Sheng MB, Vaníček P, Kingdon R, Foroughi I (2018) Rigorous evaluation of gravity field functionals from satellite-only gravitational models within topography. *IAG Symposia Series* 148: 3-7, Springer, Cham; doi: 10.1007/1345_2017_26.

38. Šprlák M, Hamáčková E, Novák P (2015) Alternative validation method of satellite gradiometric data by integral transform of satellite altimetry data. *Journal of Geodesy* 89: 757-773
39. Šprlák M, Novák P (2015) Integral formulas for computing a third-order gravitational tensor from volumetric mass density, disturbing gravitational potential, gravity anomaly and gravity disturbance. *Journal of Geodesy* 89: 141-157
40. Šprlák M, Eshagh M (2016) Local recovery of sub-crustal stress due to mantle convection from satellite-to-satellite tracking data. *Acta Geophysica* 64: 904-929
41. Šprlák M, Novák P (2016) Spherical gravitational curvature boundary-value problem. *Journal of Geodesy* 90: 727-739
42. Šprlák M, Novák P, Pitoňák M (2016). Spherical harmonic analysis of gravitational curvatures and implications for future satellite mission. *Surveys in Geophysics* 37: 681-700
43. Šprlák M, Novák P (2017) Spherical integral transforms of second-order gravitational tensor components onto third-order gravitational tensor components. *Journal of Geodesy* 91: 167-194
44. Šprlák M, Novák P (2018) Correction to: spherical gravitational curvature boundary-value problem. *Journal of Geodesy* 92: 573
45. Šprlák M, Han S-C, Featherstone W (2018) Forward modelling of global gravity fields with 3D density structures and an application to the high-resolution (~2 km) gravity fields of the Moon. *Journal of Geodesy* 92: 847-862
46. Šprlák M, Tangdamrongsub N (2018) Vertical and horizontal spheroidal boundary-value problems. *Journal of Geodesy* 92: 811-826
47. Tenzer R, Eshagh M (2015) Subduction generated sub-crustal stress in Taiwan. *Terrestrial, Atmospheric and Oceanic Sciences* 26: 261-268
48. Tenzer R, Eshagh M, Jin S (2015) Martian sub-crustal stress from gravity and topographic models. *Earth and Planetary Science Letters* 425: 84-92
49. Tenzer R, Eshagh M, Shen W (2017a) The subcrustal stress estimation in central Eurasia from gravity, terrain and crustal structure models. *Geoscience Journal* 21: 47-54
50. Tenzer R, Foroughi I, Pitoňák M, Šprlák M (2017b) Effect of the Earth's Inner Structure on the Gravity in Definitions of Height Systems. *Geophysical Journal International* 209: 297-316
51. Yang M, Hirt C, Tenzer R, Pail R (2018) Experiences with the use of mass density maps in residual gravity forward modelling. *Studia Geophysica et Geodaetica* 62: 596-623
52. Ye Z, Tenzer R, Sneeuw N (2018) Comparison of methods for a 3-D density inversion from airborne gravity gradiometry. *Studia Geophysica et Geodaetica* 62: 1-16

4.1 Selected oral and poster presentations

Foroughi I, Janák J, Kingdon RW, Sheng M, Santos M, Vaníček P (2015) Illustration of how satellite global field should be treated in regional precise geoid modelling. 12th EGU General Assembly, Vienna, April 2015.

Foroughi I, Vaníček P, Kingdon RW, Novák P, Sheng M, Santos M (2016) Poisson downward continuation of scattered Helmert’s gravity anomalies to mean values on a raster on the geoid using Least Square. 13th EGU General Assembly, Vienna, April 2016.

Foroughi I, Vaníček P, Kingdon RW, Sheng M, Santos M (2015) Assessment of discontinuity of Helmert's gravity anomalies on geoid. Canadian Geophysical Union Meeting, Montreal, Canada.

Foroughi I, Vaníček P, Novák P, Kingdon RW, Goli M, Sheng M, Santos M (2016) Harmonic downward continuation of scattered point gravity anomalies to mean anomalies on a mesh on the geoid. Canadian Geophysical Union meeting, Fredericton, Canada.

Ghobadi-Far K, Han S-C, Šprlák M (2018) A pocket guide to physical geodesy: constructing a unified scheme for representation of geopotential functionals. IX Hotine-Marussi Symposium, Rome, Italy, June 2018.

Hamáčková E, Šprlák M, Pitoňák M, Novák P (2015). Comparison of third order potential derivatives based on recent satellite-based GGMs and on global isostatic topographic models. 26th IUGG General Assembly, Prague, June-July 2015.

Holota P (2015) Summation of series and an approximation of Legendre’s functions in constructing integral kernels for the exterior of an ellipsoid: application to boundary value problems in physical geodesy. Leibniz Society of Science at Berlin, Scientific Colloquium Geodesy-Mathematic-Physics-Geophysics in honour of Erik W. Grafarend on the occasion of his 75th birthday, Berlin, Germany, February, 13, 2015. In: Kolloquium der Leibniz-Sozietät am 13. 02. 2015 zum Thema “Geodäsie-Mathematik-Physik-Geophysik”: Kurzbericht [on-line]. Leibniz-Sozietät der Wissenschaften zu Berlin, e.V.

Holota P (2017) Geodesy and Mathematics: Recent Developments in the Deep Rooted Relationship. Presented at the Wissenschaftliches Kolloquium „Die Förderung der wissenschaftlichen Geodäsie seit Friedrich Robert Helmert (1843-1917)“ organized by the Leibniz-Sozietät der Wissenschaften zu Berlin e.V. in cooperation with the Helmholtz-Zentrum Potsdam – GFZ, DVW Berlin-Brandenburg e.V. and the TU Berlin, Institut für Geodäsie und Geoinformationstechnik, Potsdam, Germany, 7 April 2017.

Holota P (2019) Divergence of gradient and the solution domain in gravity field studies. Presented at the Wissenschaftliches “Kolloquium Ein und ein halbes Jahrhundert internationale Zusammenarbeit der Geodäten und Geophysiker” organized by the Leibniz-Sozietät der Wissenschaften zu Berlin e.V. in cooperation with the Helmholtz-Zentrum Potsdam - GFZ, Potsdam, Germany, 15 February 2019.

Holota P, Nesvadba O (2015) Differential geometry of equipotential surfaces and its relation to parameters of Earth’s gravity field models. 26th IUGG General Assembly, Prague, June-July 2015.

Holota P, Nesvadba O (2015) Domain transformation and the iteration solution of boundary value problems in gravity field studies. 26th IUGG General Assembly, Prague, June-July 2015.

Holota P, Nesvadba O (2015) Elementary potentials and Galerkin’s matrix for an ellipsoidal domain in the recovery of the gravity field. 26th IUGG General Assembly, Prague, June-July 2015.

Holota P, Nesvadba O (2015) Fundamental solution of Laplace’s equation in oblate spheroidal coordinates and Galerkin’s matrix for Neumann’s problem in Earth’s gravity field studies. 12th EGU General Assembly, Vienna, April 2015.

Holota P, Nesvadba O (2016) Combining terrestrial data and satellite-only models in Earth’s gravity field studies: optimization and integral kernels. Living Planet Symposium of the European Space Agency, Prague, May 2016.

Holota P, Nesvadba O (2016) Construction of Galerkin's matrix for elementary potentials and an ellipsoidal solution domain based on series developments and general relations between Legendre's functions of the first and the second kind: application in Earth's gravity field studies. 13th EGU General Assembly, Vienna, April 2016.

Holota P, Nesvadba O (2016) Modification of ellipsoidal coordinates and successive approximations in the solution of the linear gravimetric boundary value problem. Gravity, Geoid and Height Systems 2016, Thessaloniki, Greece, September 2016.

Holota P, Nesvadba O (2016) Small modifications of curvilinear coordinates and successive approximations applied in geopotential determination. AGU Fall Meeting, San Francisco, December 2016.

Holota P, Nesvadba O (2017) Boundary complexity in classical and variational concepts of solving geodetic boundary value problems. IAG-AESPEI Joint Scientific Meeting, Kobe, July-August 2017.

Holota P, Nesvadba O (2017) Laplacian versus topography in the solution of the linear gravimetric boundary value problem by means of successive approximations. 14th EGU General Assembly, Vienna, April 2017.

Holota P, Nesvadba O (2017) Weak solution concept and Galerkin's matrix for the exterior of an oblate ellipsoid of revolution in the representation of the Earth's gravity potential by buried masses. 14th EGU General Assembly, Vienna, April 2017.

Holota P, Nesvadba O (2018) Green's function method extended by successive approximations and applied to Earth's gravity field recovery. IX Hotine-Marussi Symposium, Rome, Italy, June 2018.

Holota P, Nesvadba O (2018) Neumann's function and its derivatives constructed for the exterior of an ellipsoid and adapted to an iteration solution of the linear gravimetric boundary value problem. 15th EGU General Assembly, Vienna, April 2018.

Holota P, Nesvadba O (2018) Transformation of topography into the structure of Laplace's operator and an iteration solution of the linear gravimetric boundary value problem. 15th EGU General Assembly, Vienna, April 2018.

Holota P, Nesvadba O (2019) On the construction of Green's function when combining terrestrial data and global models for Earth's gravity field recovery. 16th EGU General Assembly, Vienna, April 2019.

Holota P, Nesvadba O (2019) Using the Green's function method for solution domains with a complicated boundary in Earth's gravity field studies. 16th EGU General Assembly, Vienna, April 2019.

Nesvadba O, Holota P (2016) An improved methodology for precise geoid/quasigeoid modelling. 13th EGU General Assembly, Vienna, April 2016.

Nesvadba O, Holota P (2016) On the downward continuation stability in dependence of the topography roughness. Gravity, Geoid and Height Systems 2016, Thessaloniki, Greece, September 2016.

Novák P (2017) Properties of gravity-field curvatures and their applications in geophysics. IAG-AESPEI Joint Scientific Meeting, Kobe, July-August 2017.

Novák P, Pitoňák M, Šprlák M (2015) Regional recovery of the disturbing gravitational potential from satellite observations of first-, second- and third-order radial derivatives of the disturbing gravitational potential. AGU Fall Meeting, San Francisco, December 2015.

Novák P, Pitoňák M, Šprlák M, Tenzer R (2018) Gravitoscopy of Earth's mass density distribution based on higher-order gradients of the gravitational potential. 15th EGU General Assembly, Vienna, April 2018.

Novák P, Pitoňák M, Tenzer R, Šprlák M (2018) Local gravitational field modelling through spectral combination of satellite higher-order radial derivatives of the disturbing gravitational potential and a global gravitational model. AGU Fall Meeting, Washington, D.C., December 2018.

Novák P, Šprlák M, Tenzer R, Pitoňák M (2016) Integral formulas for analysis of current and future satellite gravitational observations. AGU Fall Meeting, San Francisco, December 2016.

Novák P, Šprlák M, Pitoňák M, Tenzer R (2018) Classical solutions to boundary-value problems of the potential theory for current and future gravity field observables. IX Hotine-Marussi Symposium, Rome, Italy, June 2018.

Novák P, Tenzer R, Pitoňák M, Šprlák M (2016) Accuracy of classical definition of the geoid-to-quasigeoid separation. 13th EGU General Assembly, Vienna, April 2016.

Novák P, Tenzer R, Pitoňák M, Šprlák M (2016) Effect of crustal and mantle density structure on the quasigeoid-to-geoid separation. 13th EGU General Assembly, Vienna, April 2016.

Pitoňák M, Eshagh M, Novák P, Šprlák M, Tenzer R (2018) Recovery of the gravitational potential at the Earth's surface by spectral combination of first-, second- and third-order radial derivatives of the gravitational potential measured by satellite sensors. 15th EGU General Assembly, Vienna, April 2018.

Pitoňák M, Eshagh M, Novák P, Šprlák M, Tenzer R (2018) Spectral downward continuation of the first-, second- and third-order radial derivatives of the gravitational potential measured by satellite sensors. IX Hotine-Marussi Symposium, Rome, Italy, June 2018.

Pitoňák M, Eshagh M, Šprlák M, Tenzer R (2017) Spectral downward continuation of gravitational curvatures and its implications for future gravity field missions. 12th Slovak Geophysical Conference, Comenius University, Bratislava, Slovakia, September 2017.

Pitoňák M, Eshagh M, Šprlák M, Tenzer R, Novák P (2017). Spectral combination of spherical gravitational curvature boundary-value problems. 14th EGU General Assembly, Vienna, April 2017.

Pitoňák M, Novák P, Šprlák M, Eshagh M (2018) Local spectral downward continuation of the first-, second- and third-order radial derivatives of the gravitational potential onto gravity disturbances on the Earth surface. International Association of Geodesy Symposium: Gravity, Geoid and Height Systems, Copenhagen, Denmark, September 2018.

Pitoňák M, Novák P, Šprlák M, Tenzer R (2018) Combination of spherical gravitational curvatures boundary value problem using the condition adjustment model. IX Hotine-Marussi Symposium, Rome, Italy, June 2018.

Pitoňák M, Šprlák M, Hamáčková E, Novák P (2015) The effect of topographic and atmospheric masses on inversion of a satellite third-order gravitational tensor onto gravity anomalies. 26th IUGG General Assembly, Prague, June-July 2015.

Pitoňák M, Šprlák M, Novák P, Tenzer R (2016) Possibilities of the regional gravity field recovery from first-, second- and third-order radial derivatives of the disturbing gravitational potential measured on moving platforms. 13th EGU General Assembly, Vienna, April 2016.

Pitoňák M, Šprlák M, Novák P, Tenzer R (2016) Regional determination of gravity disturbances by inverting satellite gravitational gradients. Gravity, Geoid and Height Systems 2016, Thessaloniki, Greece, September 2016.

Pitoňák M, Šprlák M, Novák P (2018) Regional recovery of the disturbing gravitational potential from GOCE observables. 10 Years of the Czech Republic in ESA, Prague, November 2018.

Pitoňák M, Šprlák M, Sebera J, Novák P, Hamáčková E (2016) Comparative study of the far zones effect on the spherical downward continuation. Living Planet Symposium of the European Space Agency, Prague, May 2016.

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Šprlák M, Hájková J, Pitoňák M, Novák P, Tenzer R (2016) An analysis of geoid determination based on terrestrial observations of the radial gravity potential derivatives. 13th EGU General Assembly, Vienna, April 2016.

Šprlák M, Han S-C, Featherstone W (2018) Is the spheroidal approximation of the Moon important for high-resolution global gravitational field modelling? COSPAR 42nd Assembly, Pasadena, USA, July 2018.

Šprlák M, Han S-C, Featherstone W (2018) Regional lunar gravitational field modelling from GRAIL line-of-sight gravitation observables. IX Hotine-Marussi Symposium, Rome, Italy, June 2018.

Šprlák M, Han S-C, Featherstone W (2018) Regional Recovery of the lunar gravitational field by inverting GRAIL line-of-sight gravitation observables. COSPAR 42nd Assembly, Pasadena, USA, July 2018.

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Šprlák M, Petrš J, Pitoňák M, Novák P, Hamáčková E (2016) Possibilities of validation for GRACE satellite-to-satellite tracking data by integral transformations. Living Planet Symposium of the European Space Agency, Prague, May 2016.

Joint Study Group 0.14: Fusion of multi-technique satellite geodetic data

Chair: *Krzysztof Sośnica (Poland)*
Affiliation: *Commissions 1, 3 and 4, and GGOS*

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1. Activities

1.1 Summary

The activities of the JSG0.14 study group were concentrated around the identification of systematic effects between different techniques of satellite and space geodesy and the combination of various techniques to derive geodetic parameters. Proper identification and handling of systematics should in result improve the consistency between different observational techniques and should help us to mitigate artifacts in the geodetic time series. Therefore, different observational techniques of space geodesy, which are capable of deriving the same parameters, were cross-validated and combined. Geodetic parameters that can be determined when employing different techniques of space geodesy are thus here the fundamental subject of interest.

All of the new GNSS systems have been equipped with laser retroreflector arrays (LRA) dedicated to SLR tracking of new GNSS systems. The International Laser Ranging Service (ILRS) initiated a series of special tracking campaigns dedicated to tracking new Galileo spacecraft as well as tracking of the whole GNSS constellation. SLR observations to GNSS satellites allow for the validation of microwave-derived GNSS orbits, for the determination of GNSS orbital parameters, co-location in space on-board GNSS spacecraft and for the determination of global parameters, such as pole coordinates, length-of-day, geocenter motion, etc. The fusion of GNSS and SLR observations requires a profound investigation of biases and systematic effects affecting both techniques. Neglecting of systematic effects may lead to a degradation of solutions and the absorption of various systematic effects by global geodetic parameters.

In the framework of this Study Group, various analyses were performed including processing SLR observations to new GNSS systems, SLR observations to LEO satellites, as well as an attempt to unification and harmonization of the troposphere delay models for SLR and GNSS. For the purpose of the investigation of SLR-GNSS biases, a new on-line service has been launched (Zajdel et al. 2017): multi-GNSS Orbit Validation Visualizer Using SLR (GOVUS, www.govus.pl) as an element of the new ILRS Associated Analysis Center.

1.2 Research

Harmonization of the atmospheric delay models between SLR and GNSS

- Modeling of horizontal gradients in SLR solutions
  - Analysis of the sensitivity of SLR observations to the atmospheric asymmetry and horizontal gradients of troposphere delay
  - Estimation of horizontal gradients using SLR observations to LAGEOS-1/2 (Drożdżewski and Sośnica 2018)
  - Using GNSS-derived gradients to account for the atmosphere asymmetry in SLR solutions
  - Deriving horizontal gradients on the basis of numerical weather models (a joint activity within the framework of Joint Working Group 1.3: Troposphere ties)
- Improving mapping functions of troposphere delays
  - Using Potsdam Mapping Function (PMF) for SLR (in the framework of cooperation with GFZ Potsdam), (Sośnica et al. 2018c)
  - Using Vienna Mapping Function (VMFo) for SLR (in the framework of cooperation with TU Vienna), (Boisits et al. 2018)
  - Assimilation of numerical weather models and GNSS delays using least squares collocation (Wilgan et al. 2017a, 2017b, Wilgan and Geiger 2019)

Processing SLR observations to new GNSS systems: Galileo, GLONASS, BeiDou, QZSS

- Determination of global geodetic parameters
  - Determination of station coordinates, geocenter, and Earth rotation parameters using SLR observations to multi-GNSS satellites (Sośnica et al. 2019)
  - Determination of global geodetic parameters using SLR observations to multi-GNSS and LAGEOS satellites (Sośnica et al., 2018b)
- Analysis of the consistency between SLR and GNSS solutions
  - Analysis of the Blue-Sky effect and non-tidal surface loading displacements for SLR observations to GNSS (Bury et al. 2019a)
  - Determination of precise orbits of GNSS satellites using SLR observations (Bury et al. 2019b)
  - Development of the on-line service GOVUS.PL for the validation of multi-GNSS satellite orbits (Zajdel et al. 2017)
  - Validation and analysis of the impact of ambiguity resolution of Galileo orbits using SLR data (Katsigianni et al. 2019)
  - Quality assessment of multi-GNSS orbits using SLR for real-time Precise Point Positioning (Kaźmierski et al. 2018a, 2018b)

Integration of SLR observations to different low- and high-orbiting satellites

- Determination of the Earth’s gravity field.
- Combining SLR observations with LEO data (SWARM and GRACE) to derive time-variable Earth’s gravity field models (Meyer et al. 2019).
- Combining SLR solutions derived from different analysis centers in the framework of the EGSIEM-Follow-On activities (Bloßfeld et al. 2019).
- Applying global gravity field models for a proper georeferencing of remote sensing and GNSS data (Osada et al. 2017).

Processing of SLR observations to LEO and geodetic satellites

- Validation and calibration of SLR biases using SLR observations to LEO missions (Arnold et al. 2019).
- Validation of GOCE orbits and the sensitivity analysis of GOCE orbits to the ionospheric activity using SLR data (Strugarek et al. 2017).

- Summary on the scientific contribution of SLR observations to geodetic satellites and the quality control of SLR data (Pearlman et al. 2019, Otsubo et al. 2019).
- Determination of geocenter coordinates using GNSS-based GRACE orbits (Tseng et al. 2017).
- Determination of TOPEX/Poseidon spin parameters using high-rate SLR data (Kucharski et al. 2017).

1.3 Sessions organization at international congresses/symposia/workshops

- Co-organization of the session *X. Multi-sensor and time series data analysis (W. Kosek, K. Sośnica)* at the *IX Hotine-Marussi Symposium* (Rome, Italy) in 2018.
- Co-organization of the sessions *Geophysical Signal Separation in Global Geodesy, Observing and Separation of geophysical signals in the Climate and Earth System through Geodesy,* at the European Geoscience Union General Assembly (Vienna, Austria) in 2018 and 2019.

1.4 Technology transfer and relevant applications in science and engineering

- GOVUS (www.govus.pl): multi-GNSS Orbit Validation Visualizer Using SLR.
- GNSS-WARP: development of the software in terms of processing multi-GNSS observations in real-time (adding the possibility of processing Galileo, and BeiDou data, Kaźmierski et al. 2018a, 2018b).
- EPOS-PL: construction of co-located sites in Poland in the framework of the European Plate Observing System (EPOS), Task 8 - GGOS++. The co-located sites include: (1) precise multi-GNSS receivers, (2) tidal gravimeters gPhone-X, (3) InSAR reflectors, (4) seismometers, (5) microwave radiometers, all of which are installed in the same place. The test area is located in Southern Poland in Upper Silesia with two external reference stations in Wroclaw and Borowa Góra (Sośnica and Bosy 2019).

2. Cooperation/Interactions with IAG Commissions and GGOS

- IAG Joint Working Group 1.3: Troposphere ties – Chair: R. Heinkelmann (Germany), Vice Chair: J. Douša (Czech Republic).
- Cooperation with the ILRS and IGS MGEX (via running the GOVUS service and the Associated ILRS Analysis Center for the validation of multi-GNSS orbits).

3. Future prospects

3.1 Research

Determination of global geodetic parameters using combined SLR-GNSS observations

- Determination of geocenter motion from Galileo, GPS, GLONASS, and BeiDou.
- Analysis of daily pole coordinates and length-of-day variations using combined SLR-GNSS observations to Galileo.
- Determination of sub-daily Earth Rotation Parameters from SLR, Galileo and other GNSS systems.
- Co-location in space between SLR and GNSS using Galileo and GLONASS satellites.
- Precise orbit determination of GNSS satellites using combined SLR and microwave observations.
- Deriving geodetic parameters using GNSS employing time-variable gravity field models derived from SLR and GRACE.

Integration of SLR observations to active LEO, geodetic, and GNSS satellites

- Combination of SLR observations to various LEO missions: Sentinel-3A/3B, GRACE, GRACE-FO, GOCE, SWARM-A/B/C, Jason-2/3 to derive global geodetic parameters and to realize the terrestrial reference frames.
- Time-variable gravity field determination using SLR observation to passive geodetic satellites (LAGEOS-1/2, LARES-1/2, Starlette, Stella, Ajisai, Larets, BLITS-M, BLITS).
- Orbit simulations and processing data from new satellite missions planned for 2019: LARES-2, BLITS-M, and launched in 2018: Sentinel-3B, GRACE-FO.
- Time-variable gravity field determination using SLR observation to passive geodetic satellites and GNSS-based orbits of LEO satellites to fill the gap between GRACE and GRACE-FO missions.
- Combinations between GRACE-FO results and SLR for the improvement of degree-2 gravity field parameters.

Atmospheric delay modeling issues

- Development of a simple model of troposphere horizontal gradients for SLR solutions (which is important in the context of including LARES-1 into the operational ILRS products).
- Homogenization of troposphere delay models for co-located space geodetic stations. Using the same troposphere parameters for estimating the hydrostatic delay in SLR and GNSS solutions.

3.2 Sessions organization at international congresses/symposia/workshops

- Organization of a session on the integration of space geodetic techniques at the *X Hotine-Marussi Symposium* in 2022.
- Co-organization of the session at next *European Geoscience Union General Assembly* and *IAG Commission 4 Symposium*.

3.3 Editorial activity

- Special issues on peer-review journals on the integration of SLR, multi-GNSS, LEO and gravity field data.
- JSG publications: proposal for review papers on integration of various techniques of space geodesy co-authored by the JSG members.

3.4 Technology transfer and relevant applications in science and engineering

- Reference bibliography on multi-GNSS, SLR, LEO, and time-variable gravity
- Publication of Galileo, GLONASS, and BeiDou orbits derived using combined SLR and GNSS observations (contribution to IGS MGEX and ILRS)
- Extension of the on-line service GOVUS

4. Publications

1. Arnold D, Montenbruck O, Hackel S, Sośnica K (2019) Satellite laser ranging to low Earth orbiters: orbit and network validation. *Journal of Geodesy*; doi: 10.1007/s00190-018-1140-4.

2. Bloßfeld M, Meyer U, Sośnica K, Jäggi A (2019) Combined SLR gravity field time series for continuous Earth System Monitoring. European Geosciences Union General Assembly 2019, Vienna, Austria, 7-12 April 2019. *Geophysical Research Abstracts.*

3. Boisits J, Landskron D, Sośnica K, Drożdżewski M, Böhm J (2018) VMF3o: enhanced tropospheric mapping functions for optical frequencies. 21st International Workshop on Laser Ranging, Canberra, Australia, 4-9 November 2018.
4. Bury G, Sośnica K, Zajdel R (2019a) Impact of the atmospheric non-tidal pressure loading on global geodetic parameters based on satellite laser ranging to GNSS. *IEEE Transactions on Geoscience and Remote Sensing*: 1-17; doi: 10.1109/TGRS.2018.2885845.
5. Bury G, Sośnica K, Zajdel R (2019) Multi-GNSS orbit determination using satellite laser ranging. *Journal of Geodesy*; doi: 10.1007/s00190-018-1143-1.
6. Drożdżewski M, Sośnica K (2018) Satellite laser ranging as a tool for the recovery of tropospheric gradients. *Atmospheric Research* 212: 33-42; doi: 10.1016/j.atmosres.2018.04.028.
7. Katsigianni G, Loyer S, Perosanz F, Mercier F, Zajdel R, Sośnica K (2019) Improving Galileo orbit determination using zero-difference ambiguity fixing in a Multi-GNSS processing. *Advances in Space Research* 63(9): 2952-2963; doi: 10.1016/j.asr.2018.08.035
8. Kaźmierski K, Sośnica K, Hadaś T (2018a) Quality assessment of multi-GNSS orbits and clocks for real-time Precise Point Positioning. *GPS Solutions* 22: 1-12, Berlin – Heidelberg; doi: 10.1007/s10291-017-0678-6.
9. Kaźmierski K, Hadaś T, Sośnica K (2018b) Weighting of multi-GNSS observations in real-time precise point positioning. *Remote Sensing* 10(1): 1-12, Basel, Switzerland; doi: 10.3390/rs10010084.
10. Kucharski D, Kirchner G, Bennett J. C, Lachut M, Sośnica K, Koshkin N, Shakun L, Koidl F, Steindorfer M, Wang P et al. (2017) Photon pressure force on space debris TOPEX/Poseidon measured by Satellite Laser Ranging. *Earth and Space Science* 4: 661-668; doi: 10.1002/2017EA000329.
11. Meyer U, Sośnica K, Arnold D, Dahle C, Thaller D, Dach R, Jäggi A (2019) SLR, GRACE and Swarm gravity field determination and combination. *Remote Sensing* 11: 956; doi: 10.3390/rs11080956.
12. Osada E, Sośnica K, Borkowski A, Owczarek-Wesołowska M, Gromczak A (2017) A direct georeferencing method for terrestrial laser scanning using GNSS data and the vertical deflection from global earth gravity models. *Sensors* 17(7); doi: 10.3390/s17071489.
13. Otsubo T, Müller H, Pavlis EC, Torrence MH, Thaller D, Glotov VD, Wang X, Sośnica K, Meyer U, Wilkinson MJ (2019) Rapid response quality control service for the laser ranging tracking network. *Journal of Geodesy*; doi: 10.1007/s00190-018-1197-0.
14. Pearlman M, Arnold D, Davis M, Barlier F, Biancale R, Vasiliev V, Ciufolini I, Paolozzi A, Pavlis EC, Sośnica K, Bloßfeld M (2019) Laser geodetic satellites: a high-accuracy scientific tool. *Journal of Geodesy*; doi: 10.1007/s00190-019-01228-y.
15. Sośnica K, Prange L, Kaźmierski K, Bury G, Drożdżewski M, Zajdel R, Hadaś T (2018a) Validation of Galileo orbits using SLR with a focus on satellites launched into incorrect orbital planes. *Journal of Geodesy* 92(2): 131-148; doi: 10.1007/s00190-017-1050-x.
16. Sośnica K, Bury G, Zajdel R (2018b) Contribution of multi-GNSS constellation to SLR-derived terrestrial reference frame. *Geophysical Research Letters* 45(5): 2339-2348; doi: 10.1002/2017GL076850.

17. Sośnica K, Drożdżewski M, Bury G, Zus F (2018c) Atmospheric delay modeling with horizontal gradients for SLR observations. European Geosciences Union General Assembly 2018, Vienna, Austria, 8-13 April 2018.
18. Sośnica K, Bury G, Zajdel R, Strugarek D, Drożdżewski M, Kaźmierski K (2019) Estimating global geodetic parameters using SLR observations to Galileo, GLONASS, BeiDou, GPS, and QZSS. *Earth, Planets and Space* 71(20): 1-11; doi: 10.1186/s40623-019-1000-3.
19. Sośnica K, Bosy J (2019) Global Geodetic Observing System 2015-2018. *Geodesy and Cartography* 68(1): 37-60; doi: https://doi.org/10.24425/gac.2019.126090.
20. Strugarek D, Sośnica K, Jäggi A (2019) Characteristics of GOCE orbits based on Satellite Laser Ranging. *Advances in Space Research* 63(1): 417-431; doi: 10.1016/j.asr.2018.08.033.
21. Tseng TP, Hwang C, Sośnica K, Kuo CY, Liu YC, Yeh WH (2017) Geocenter motion estimated from GRACE orbits: the impact of F10.7 solar flux. *Advances in Space Research* 59(11): 2819-2830; doi: 10.1016/j.asr.2016.02.003.
22. Wilgan K, Hurter F, Geiger A et al. (2017a) Tropospheric refractivity and zenith path delays from least-squares collocation of meteorological and GNSS data. *Journal of Geodesy* 91: 117; doi: 10.1007/s00190-016-0942-5.
23. Wilgan K, Hadas T, Hordyniec P et al. (2017b) Real-time precise point positioning augmented with high-resolution numerical weather prediction model. *GPS Solutions* 23(3); doi: 10.1007/s10291-017-0617-6.
24. Wilgan K, Geiger A (2019) High-resolution models of tropospheric delays and refractivity based on GNSS and numerical weather prediction data for alpine regions in Switzerland. *Journal of Geodesy*; doi: 10.1007/s00190-018-1203-6.
25. Zajdel R, Sośnica K, Bury G (2017) A new online service for the validation of multi-GNSS orbits using SLR. *Remote Sensing* 9(10): 1-22; doi:10.3390/rs9101049.

Joint Study Group 0.15: Regional geoid/quasi-geoid modelling – theoretical framework for the sub-centimetre accuracy

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1. Activities

1.1 Summary

A theoretical framework for the regional geoid/quasi-geoid modelling is a conceptual structure to solve a geodetic boundary value problem regionally. They consist of, but are not limited to, the following components:

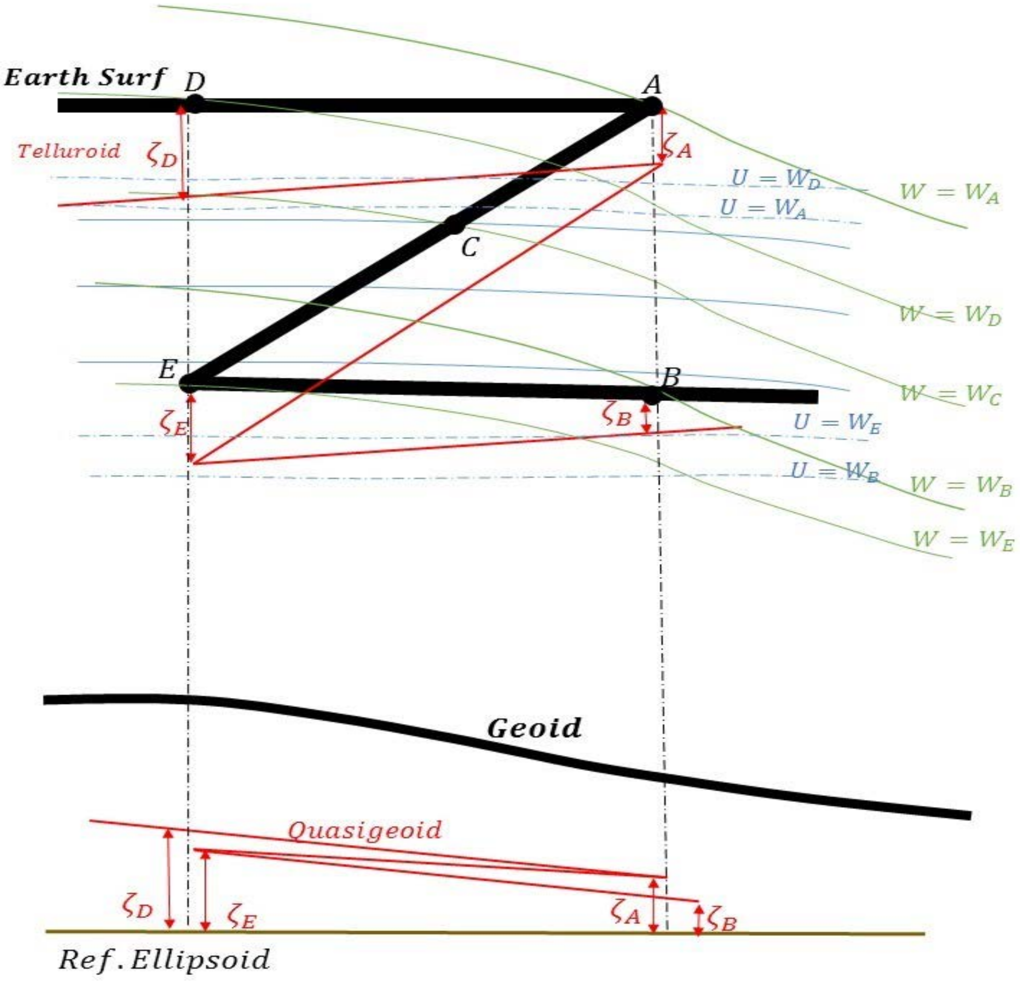
- Physical constant GM
- W0 convention and changes
- Geodetic Reference Systems and Frames such as GRS80 and ITRF
- Formulation of the geodetic boundary value problem (GBVP)
- Numerical methods
- Data type, distribution and quality requirements
- Gravity reduction
- Data interpolation and extrapolation methods
- Combination of different types of gravity data
- Estimation of the geoid/quasi-geoid model error
- Validation of geoid/quasi-geoid models
- Transformation between the geoid and quasi-geoid models
- Time-variable geoid/quasi-geoid modelling
- New theories and methods such as the radial basis functions (RBFs).

For the period of 2015-2019, members of the JSG have contributed to seven of these components which are highlighted in Section 1.2.

1.2 Research

Formulation of the geodetic boundary-value problem (GBVP)

- When computing the geoid for Auvergne, Janak et al. (2017) and Foroughi et al. (2017a) were naturally interested in comparing their results with the best results for the quasigeoid. They reported that the geoid appears to be determinable to a higher accuracy than the quasigeoid. One of the first things they discovered is showed in the figure below; referred as folded quasigeoid. This research continues in (Kingdon et al. 2018).



Data type, distribution and quality requirements

- Huang et al. (2017) compared GRAV-D data with terrestrial gravity data in three survey blocks that cross the Canada-US border, and showed that differences between GRAV-D and terrestrial gravity data are 3.6 mGal for AN04, 1.8 mGal for EN05 and 2.3 mGal for EN08 in terms of Root Mean Square (RMS) at the mean flight height.
- Barzaghi et al. (2018) computed geoid models for the Mediterranean using the remove-compute-restore Stokes-FFT method, and shipborne gravity or altimetry inferred gravity data over sea and land gravity data. The remove step over sea does not include residual terrain correction (bathymetry), which leads to slightly worse results. The models were compared to an independent geoid constructed by subtracting the Mean Dynamic Topography from the Mean Sea Surface, and secondly to drifter-observed current speeds. Results revealed significant errors in the gravimetric geoid at smallest scales, and analysis of the results of this intermediate model showed that improvement is required in the gravity data preprocessing, specifically the de-biasing of marine data, as well as the gridding (interpolation) procedure.

Gravity reduction

- Kingdon et al. (2015) studied least-squares downward continuation of gravity anomalies in Helmert’s space, introducing the concept and showing some sample applications.
- Vaníček et al. (2016) discovered that during the iterative solution of the downward continuation problematic unique inverse problem – the solution stays within physically meaningful boundaries. As starting from some iteration, the process starts to model the

effect of random errors and thus it makes no sense to seek an exact solution; instead the most probable solution in statistical sense should be preferred.

- Tavakoli et al. (2016) did a study of an application of Kouba’s refined form of Poisson’s partial differential equation of the gravity potential to the problem of topographical density determination.
- Vaníček et al. (2018) have done some additional thinking about the origin of the secondary indirect topographical effect (SITE).
- Foroughi et al. (2018a, b) developed an algorithm to get the minimum quadratic norm values (least-squares estimates) of downward continued Helmert’s gravity anomalies, which under the assumption of Gaussian distribution of errors are the most probable estimates of the real downward continued anomalies. In application for Auvergne in France, the mean standard deviations of the geoidal heights are only 0.6 cm. As one should expect, the main contributing factors to these uncertainties are the Poisson probabilistic downward continuation process, with the maximum standard deviation just short of 6 cm (the average value of 2.5 mm) and the topographic density uncertainties, with the maximum value of 5.6 cm (the average value of 3.0 mm).
- Sheng et al. (2019a) have produced a global laterally-varying topographical density model with 30 arc-second, 5 arc-minute, and 1 arc-degree angular grid resolutions by associating a global lithology model with appropriate densities determined from geological databases.
- Lin and Denker (2019) investigated the computation of topographic and atmospheric effects with tesseroids.

Combination of different types of gravity data

- Wang et al. (2016) discussed two methods of combination: the spectral combination and the least-squares collocation with emphasis on the first. The method was applied for satellite, airborne and terrestrial gravity data in the US NGS’s GSVS11 (Jiang and Wang 2016).
- Gerlach and Ophaug (2017) derived combined geoid solutions from state-of-the-art satellite only models (based on Release-5 GOCE data) and terrestrial information. Combination was performed in the spectral domain using Wenzel's stochastic method as well as more deterministic methods like the classical Wong&Gore modification. Wenzel's approach was chosen, because it is considered to be optimal in a certain sense. Thereby it is important to stress, that correlated noise for both satellite and terrestrial data have been assumed. Comparison with older geoid models shows the general improvement brought by the satellite missions GRACE and GOCE from around 8 cm before GRACE and GOCE, to currently around 3 cm.
- Huang and Véronneau (2017) studied the spectral response of Stokes’s integral to its modification and truncation. They suggest that the unmodified Stokes’s integral is spectrally unstable when being arbitrarily truncated, and a modification to Stokes‘s kernel is required for a smooth geoid model.

Estimation of the geoid/quasi-geoid model error

- Featherstone et al. (2018) published the first Australian gravimetric quasigeoid model with location-specific uncertainty estimates. The gravimetric quasigeoid errors (one sigma) are 50–60 mm across most of the Australian landmass, increasing to ∼100 mm in regions of steep horizontal gravity gradients or the mountains, and are commensurate with external estimates.
- Gerlach et al. (2019) have tried to derive general measures for the errors of geoid and gravity anomalies based on different sets of input data (a coarse and dense grid of scattered gravity data in a test area in Norway, point dsitance around 6 and 2-3 km, respectively). The main focus is on the representation error. The error estimates, derived by least-squares collocation, are general in the sense that we used a band-pass filtered

global covariance function instead of empirical regional functions. Validation with independent data shows, that the signal variance in the area fits our general model and that formal error estimates for gravity anomalies and geoid heights correspond well with the empirical errors. Finally, we expect that the denser gravity dataset can improve the geoid from around 2 to almost 1 cm.

Validation of geoid/quasi-geoid models

- Santos et al. (2015) reported a series of comparisons of geoidal heights derived from several GOCE models with (1) geoidal heights derived from GPS on benchmarks (referred to as geometric geoidal heights) over Mexico and Canada, and with (2) geoidal heights derived from the latest geoidal maps of Mexico (GGM2010) and Canada (PCGG2013). The omission errors in Mexico and in Canada show a similar behavior, with a near zero mean and a standard deviation at the order of ˙50 cm in Mexico and ˙45 cm in Canada.
- In the Great Lakes region, the improvement of the geoid model by GRAV-D reaches decimetres using the lake surface height measured by satellite altimetry as an independent data set over Lake Michigan where the legacy gravity data have significant errors (Li et al. 2016).
- In Perth, Western Australia, a modern digital astro-geodetic field campaign was completed in February 2017. Along a ~40 km long east-west traverse crossing the Perth Basin, vertical deflection data were collected at 37 field stations using two Q-Daedalus digital astronomical measurement systems (Guillaume and Bürki 2014; Hauk et al. 2016). The initial analysis of these new vertical deflection data indicates a precision of 0.2 arc-sec.

New theories and methods

- Ophaug and Gerlach (2017) investigated the equivalence of these three methods (Stokes integration, least-squares collocation and representation in spherical splines) in regional applications both from a theoretical as well as from a numerical point of view. They found that all methods agree on the sub-millimeter to millimeter level, where the largest deviations are due to discretization errors of Stokes integral equation.
- Lin et al. (2019) compared the fixed and free-positioned point mass methods for the RBF modeling of regional gravity fields, and suggested that the latter outperforms the former in regions with rough field features.
- While attempting to provide a solution to the polar gap problem that contaminates the GOCE mission data, Sheng et al. (2019b) extended the work of Paul (1973) and developed two theorems for formulating the global spherical harmonic series exactly from any number of sub-regions (of any arbitrary shape) completely covering the globe without overlap; the first theorem for the 2D case and the second dealing with the more general 3D case. They also investigated the numerical evaluation of these theorems using synthetic data to demonstrate that the inconsistencies between theory and practice do not unduly contaminate the results.

1.3 Sessions organization at international congresses/symposia/workshops

- Co-organization of the session *Deformation and gravity field modelling at regional scales (J. Huang, Y. Tanaka) a*t the *IX Hotine-Marussi Symposium* (Rome, Italy) in 2018.

2. Cooperation/Interactions with IAG Commissions and GGOS

The JSG0.15 has been collaborating closely with the following groups and sub-commissions (SC) in organizing an international cooperation on determining the best ways to combine satellite gravity models and terrestrial/airborne gravity data in geoid modelling and work towards a 1 cm accuracy goal in Colorado, USA:

- GGOS JWG: Strategy for the Realization of the IHRS (chair L. Sánchez)
- IAG SC 2.2: Methodology for geoid and physical height systems (chair J. Agren)
- IAG JWG 2.2.2: The 1 cm geoid experiment (chair Y. M. Wang)

3. Publications

1. Barzaghi R, Carrion D, Vergos GS et al. (2018) GEOMED2: High-Resolution Geoid of theMediterranean, *IAG Symposia Series*; https://doi.org/ 10.1007/1345_2018_33, Springer

2. Featherstone WE, McCubbine JC, Brown NJ et al. (2018) The first Australian gravimetric quasigeoid model with location-specific uncertainty estimates. *Journal of Geodesy* 92: 149; https://doi.org/10.1007/s00190-017-1053-7.

3. Foroughi I, Vaníček P, Sheng M, Kingdon R, Santos M (2017a) In defense of the classical height system. *Geophysical Journal International*, https://doi.org/10.1093/gji/ggx366.

4. Foroughi I, Vaníček P, Kingdon R, Sheng M, Santos MS (2018a) Investigating the accuracy of the Poisson's downward continuation using least squares technique. IX Hotine-Marussi Symposium, Rome, Italy, June 18-22.

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8. Huang J, Véronneau M (2017) The spectral response of Stokes's integral to modification and truncation, a commemorative publication for Bernhard Heck. KIT, 117-121; doi: Einzelbeitrag:10.5445/KSP/1000080220.

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11. Janák J, Vaníček P, Foroughi I, Kingdon R, Sheng M, Santos MC (2017) Computation of precise geoid model of Auvergne using current UNB Stokes-Helmert's approach. *Contributions to Geophysics and Geodesy* 47(3): 201-229; doi :10.1515/congeo-2017-001

12. Kingdon R, Vaníček P, Zhong D (2015) Least squares downward continuation, fusion and gridding of airborne and terrestrial gravity observations. Presented at the IUGG General Assembly, Prague, June 22 to July 2.

13. Kingdon R, Vaníček P, Santos MC (2018) The shape of the quasi-geoid. IX Hotine-Marussi Symposium, oral presentation, Rome, Italy, June 18-22.

14. Lin M, Denker H. Müller J (2019) A comparison of fixed- and free-positioned point mass methods for regional gravity field modelling. *Journal of Geodynamics* 125: 32-47; doi: 10.1016/j.jog.2019.01.001.

15. Lin M, Denker H (2019) On the computation of gravitational effects for tesseroids with constant and linearly varying density. *Journal of Geodesy* 93: 723-747; https://doi.org/10.1007/s00190-018-1193-4.
16. Ophaug V, Gerlach C (2017) On the equivalence of spherical splines with least-squares collocation and Stokes's formula for regional geoid computation. *Journal of Geodesy*; doi: 10.1007/s00190-017-1030-1.
17. Santos MC, Avalos D, Peet T, Sheng M, Kim D, Huang J (2015) Assessment of GOCE models over Mexico and Canada and impact of omission errors. *IAG Symposia Series*143; doi:10.1007/1345_2015_28, Springer International Publishing Switzerland.
18. Sheng MB, Vaníček P, Kingdon RW, Foroughi I (2017) Rigorous evaluation of gravity field functionals from satellite-only gravitational models within topography. *IAG Symposia Series*. 1st Joint Commission 2 and IGFS Meeting – International Symposium on Gravity, Geoid, and Height Systems, Thessaloniki, Greece. Springer.
19. Sheng MB, Shaw C, Vaníček P, Kingdon RW, Santos M, Foroughi I (2019) Formulation and validation of a global laterally varying topographical density model. *Tectonophysics* (in press).
20. Sheng MB, Vaníček P, Novák P, Santos MC, Kingdon RW, Foroughi I (2019b) Per partes integration of potential coefficients in global spherical harmonic series. Submitted to *Journal of Geodesy*.
21. Tavakoli A, Safari A, Vaníček P (2016) A special case of the Poisson PDE for formulated Earth's surface and its capability to approximate the terrain mass density employing land-based gravity data, a case study in the south of Iran. *Geophysical Journal International* 207(3): 1529-1553
22. Vaníček P, Novák P, Sheng MB, Kingdon R, Janák J, Foroughi I, Martinec Z, Santos MC (2016) Does Poisson's downward continuation give physically meaningful results? *Studia Geophysica et Geodaetica*; doi: 10.1007/s11200-016-1167-z.
23. Vaníček P, Kingdon R, Vajda P, Huang J (2018) What is the real meaning of the secondary indirect effect? Poster presentation at the IAG-IASPEI Joint Scientific Assembly (will appear in the proceedings), Kobe, Japan, July 30 to August 4, 2018.
24. Wang YM, Huang J, Jiang T, Sideris MG (2016) Local geoid determination. *Encyclopaedia of Geodesy*, Springer; doi: 10.1007/978-3-319-02370-0_53-1.

Joint Study Group 0.16: Earth's inner structure from combined geophysical sources

Chair: *Robert Tenzer (Hong Kong)*
Affiliation: *Commissions 2 and 3*

Members

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Mohammad Bagherbandi (Sweden)
Carla Braitenberg (Italy)
Mirko Reguzzoni (Italy)
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1. Activities

1.1 Summary

Seismological, gravity, magnetotelluric and heat flow measurements are mainly used to investigate Earth's inner structure. Seismic tomography (especially surface waves) and seismic reflection and refraction experiments provide images of inner structure, importantly of density interfaces (sediment basements, Moho, lithosphere-asthenosphere boundary LAB, core-mantle boundary zone). Seismic velocities could also be inverted for density and temperature, and seismic attenuation and seismic anisotropy are correlated with temperature and strain, respectively. Global heat flow measurements help constrain the lithospheric geotherm and Earth's energy budget. Magnetotelluric studies image Earth's electrical conductivity. Gravity field manifests Earth's density structure and this information is used in studies of isostasy, lithospheric stresses, basement morphology, seafloor relief, or lithospheric elastic thickness.

Scientific activities of the members of this study group reflect their expertise primarily in gravimetry and seismology. The study group focused on theoretical and practical research aspects, involving developments and applications of theoretical models for gravity inversion, seismic data processing and analysis, the combination of seismic and gravity data, and the facilitation of various geophysical and geodetic data in studies of Earth's structure and processes. They extensively applied existing and newly developed theoretical models in geodynamic and geophysical interpretations of Earth's interior. Studies (listed below) involve, for instance, the modelling of Moho interface, LAB, lithospheric stresses, or oceanic slabs. Moreover, they investigated oceanic lithosphere, mantle structure, inner-inner core equatorial anisotropy, orogenic formations and crustal melting beneath them, mantle viscosity, sedimentary basins, metallogenic zones in cratonic formations, and many other phenomena. In addition to terrestrial studies, their research involved some planetary applications. Selected research outcomes are briefly summarized next.

1.2 Research

In selected examples from scientific outputs, we demonstrate global and regional gravity images of Earth's crust and upper mantle, the Moho models from combined processing of gravity and seismic data, global maps of stress field of Venus, Mars and Earth, and the regional study of horizontal stresses in Fennoscandia. Theoretical examples are given for the definition of height reference systems and the computation of Bouguer gravity field of telluric planets (and Earth's Moon). We also present the recent development in the Bayesian gravity inversion and its application.

Global gravimetric studies

Chen and Tenzer (2019) compiled and interpreted global mantle and sub-lithosphere mantle gravity maps, see Fig. 1. They identified global lateral thermal distribution within the asthenosphere and negative thermal anomalies of subducted slabs in West Pacific, see Fig. 1d.

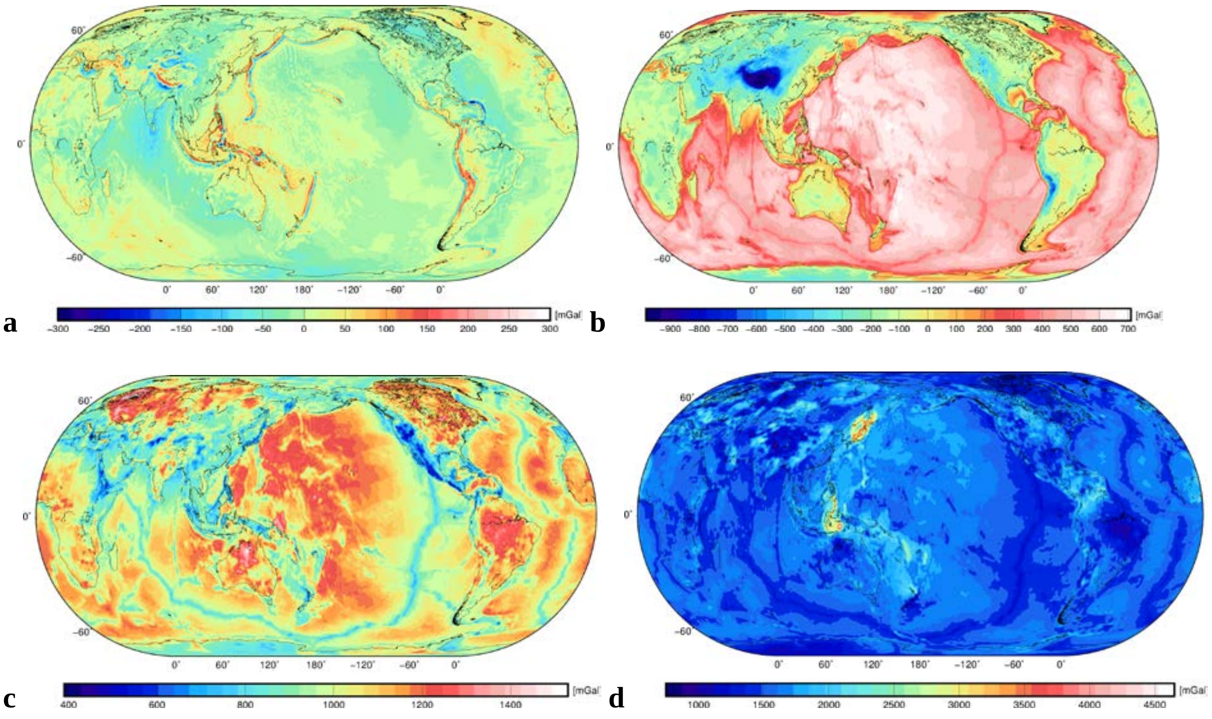


Figure 1: Global gravity: (**a**) free-air, (**b**) Bouguer, (**c**) mantle and (**d**) sub-lithosphere mantle.

Detailed regional gravimetric studies

Numerous studies were dedicated to investigate geologically and tectonically significant regions, such as Tibet, West Pacific, the South China Sea, or Iran. We also conducted large-scale studies. Rathnayake et al. (2019) compiled and interpreted the Bouguer and mantle gravity maps of the Indian Ocean, see Fig. 2. They demonstrated that the southern Nubian-Somalian plate boundary, i.e., the Lwandle plate, and the Indo-Australian plate boundary, i.e., the Capricorn plate, are not manifested in the mantle gravity map by a thermal signature, confirming that these tectonic margins are diffuse zones of convergence, characterized by low deformation and seismicity due to very slow rates of relative motions accommodated across these boundaries. They also show that a thermal signature of intraplate hotspots in the mantle gravity map is almost absent. This finding agrees with the evidence from direct heat flow measurements that do not indicate the presence of a significant positive temperature anomaly compared to the oceanic lithosphere of a similar age.

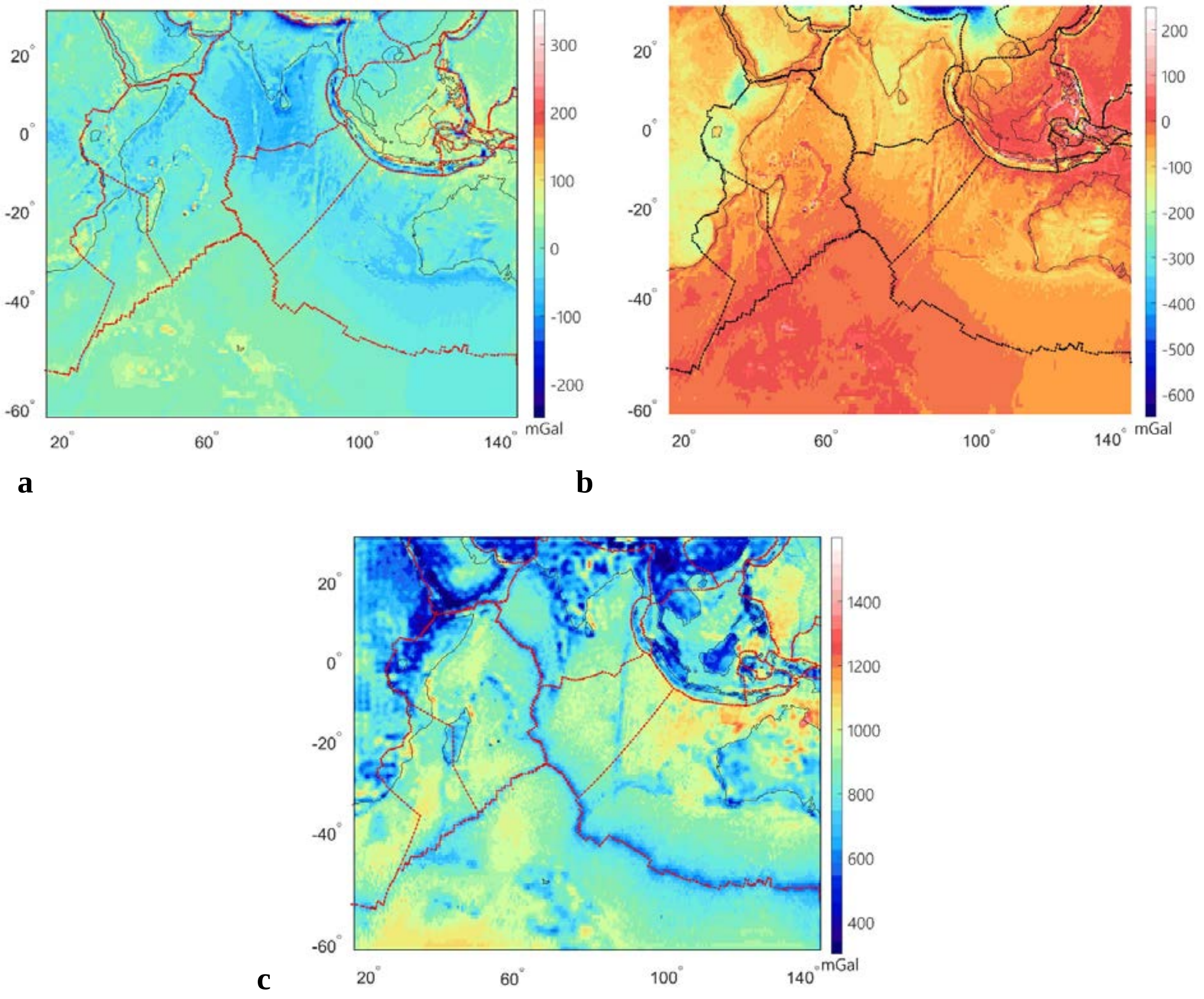


Figure 2: Gravity of the Indian Ocean: (a) free-air, (b) Bouguer and (c) mantle gravity data.

Regional crustal models

We compiled several regional Moho models using gravity and seismic data, and conducted similar continental-scale studies. In Figs. 3 and 4, the example is shown for the Moho depth in Antarctica estimated by Baranov et al. (2018). Bagherbandi et al. (2017) investigated the contribution of the lithospheric thermal state on the Moho geometry in South America, see Fig. 5. Another area of study of density modeling incorporating seismic velocity models or information was the Alps, as well as the Chad basin (manuscripts in preparation stage).

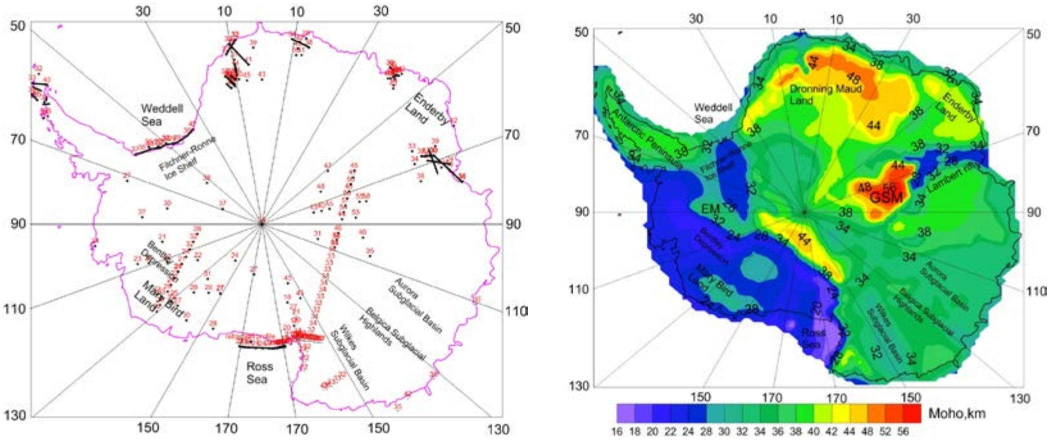


Figure 3: Seismic data (left) and the seismic Moho model (right) of Antarctica.

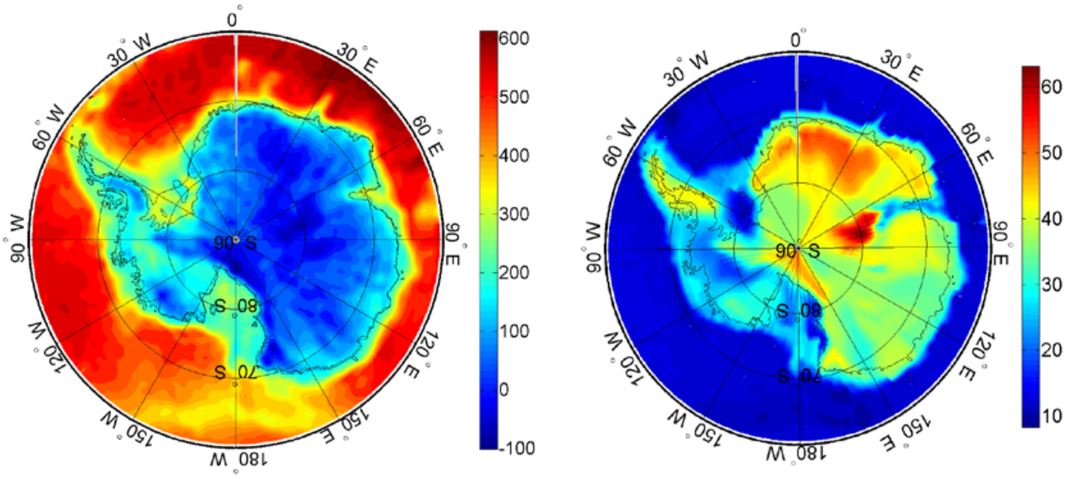


Figure 4: Bouguer gravity data (left) and the **c**ombined Moho model (right) of Antarctica.

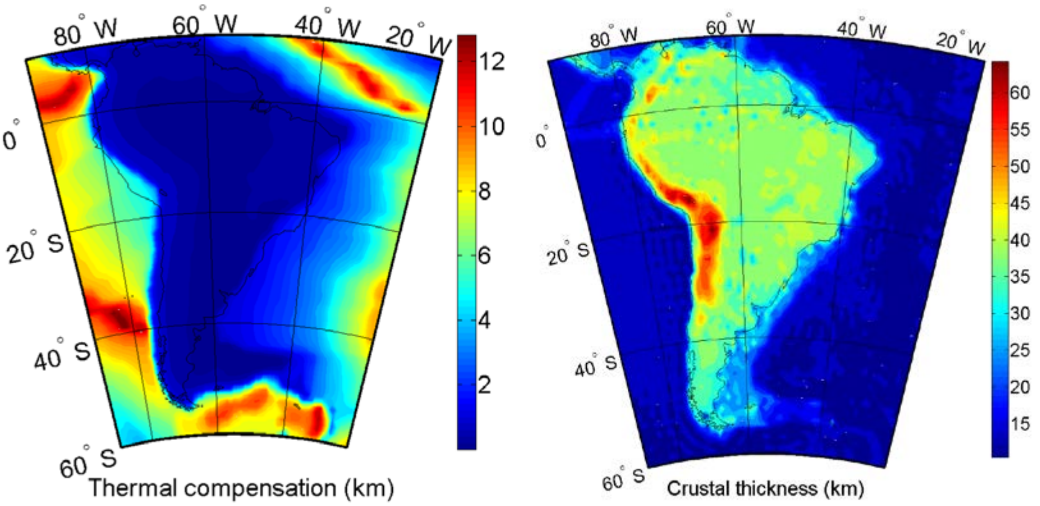


Figure 5: The lithospheric thermal-pressure compensation on the Moho depth (left) and the Moho model (right) of South America.

Stress field studies

Tenzer et al. (2015), Eshagh and Tenzer (2015) and Zampa et al. (2018) investigated a possible evidence of global tectonism on Venus and Mars. They used gravity and topographic models to compute stress field. According to their results, the signature of global tectonism on Mars and Venus is absent, see Fig. 6a, b, while the global tectonic configuration is clearly manifested in terrestrial stress field anomalies, see Fig. 6c.

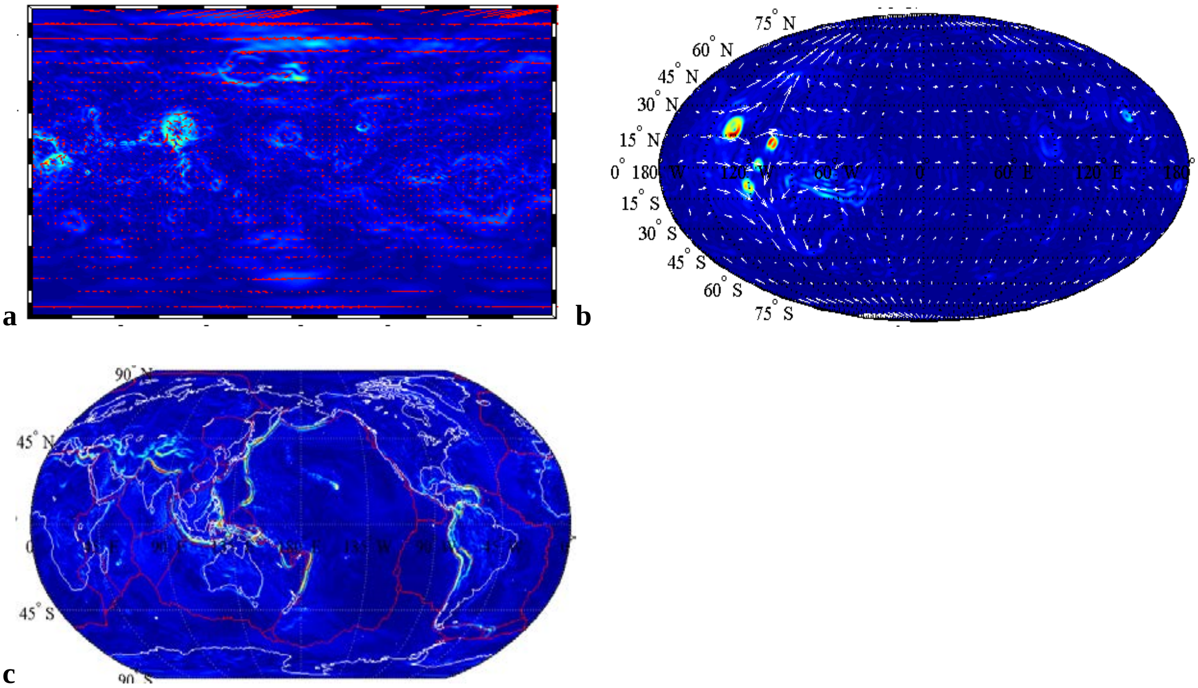
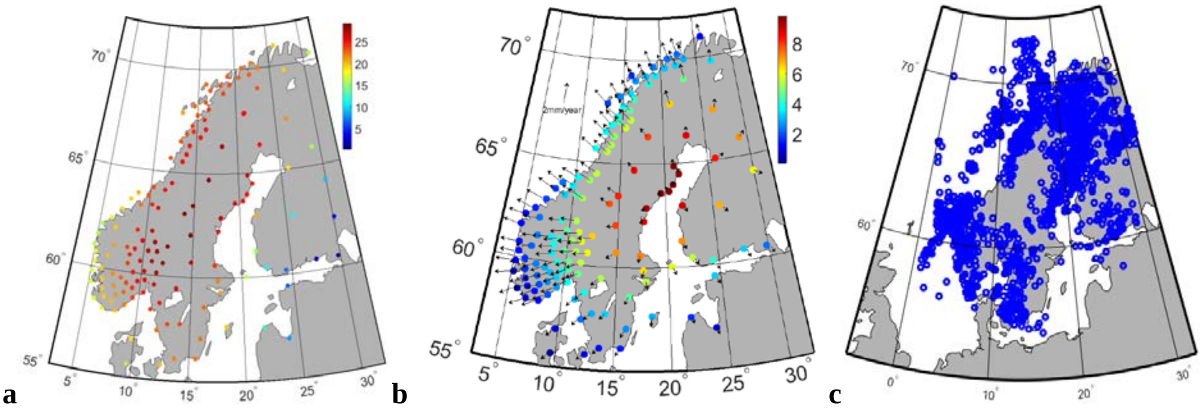


Figure 6: The global stress maps of (**a**) Venus, (**a**) Mars and (**c**) Earth.

Gido et al. (2018) determined the horizontal stress field induced by mantle convection in Fennoscandia using gravity data, see Fig. 7. The result is consistent with tectonism and seismicity of the region. In addition, the secular rate of change of the horizontal stress, which is within 95 kPa/year, is larger outside the uplift dome than inside.



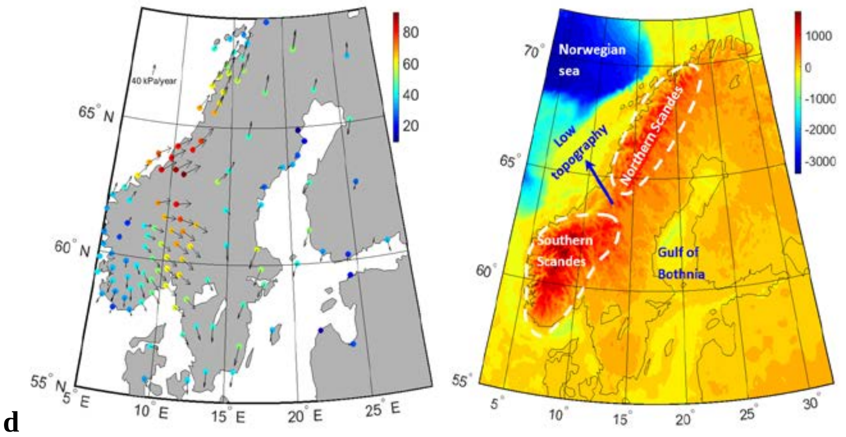


Figure 7: Horizontal stress field in Fennoscandia: (**a**) the absolute horizontal stress (in MPA) from gravity data, (**b**) the vertical (color circles) and horizontal (black arrows) velocities (in mm/yr) from GPS results and ICE-5G-FEM model (Kierulf et al. 2014), (**c**) the seismic activity between 2007-2017 according to FENTEC (Finnish Institute of Seismology, University of Helsinki) database, and (**d**) the secular rate of horizontal stress (tectonics) shown in color circles (in kPa/yr) and its direction changes with black arrows (in mm/yr). Right panel shows topography (in m).

Planetary studies

In theoretical study by Tenzer et al. (2018), authors discussed definitions of height systems for telluric planets (and Earth's Moon). They proposed a more accurate approach for defining the physical (orthometric) heights with respect to the geoid surface, see Fig. 8. They also demonstrated that the accuracy of computing physical heights could be improved, see Fig. 9.

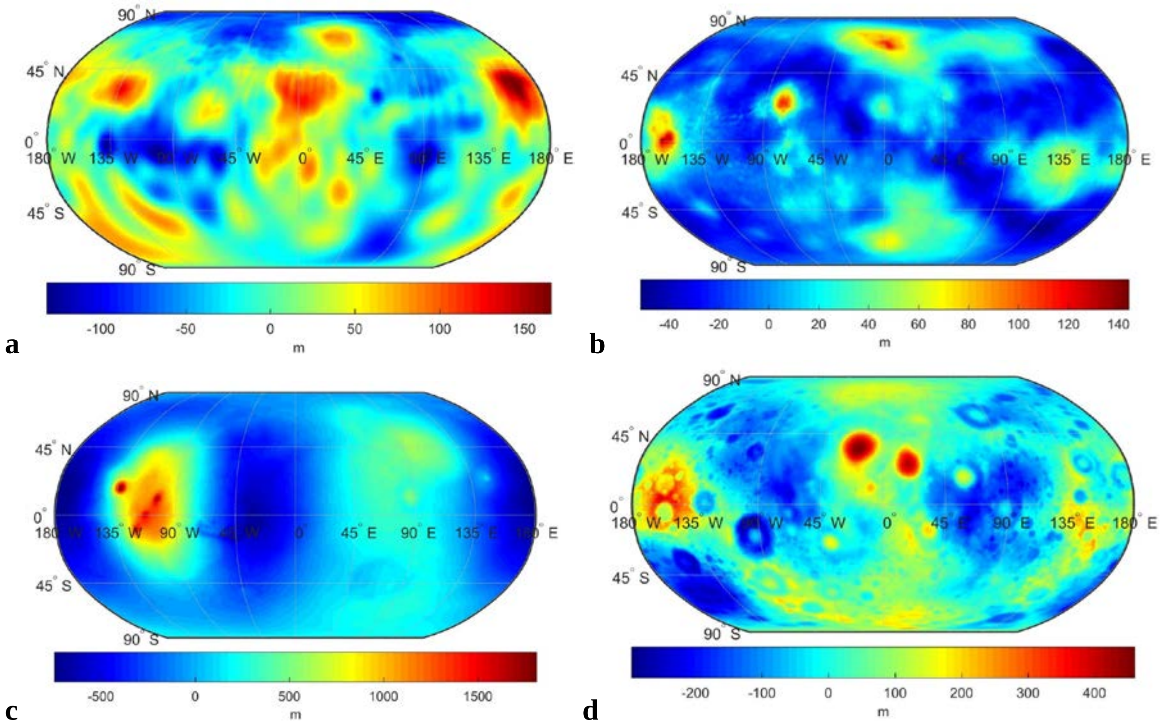


Figure 8: Geoidal heights on (a) Mercury, (b) Venus, (c) Mars and (d) Earth's Moon.

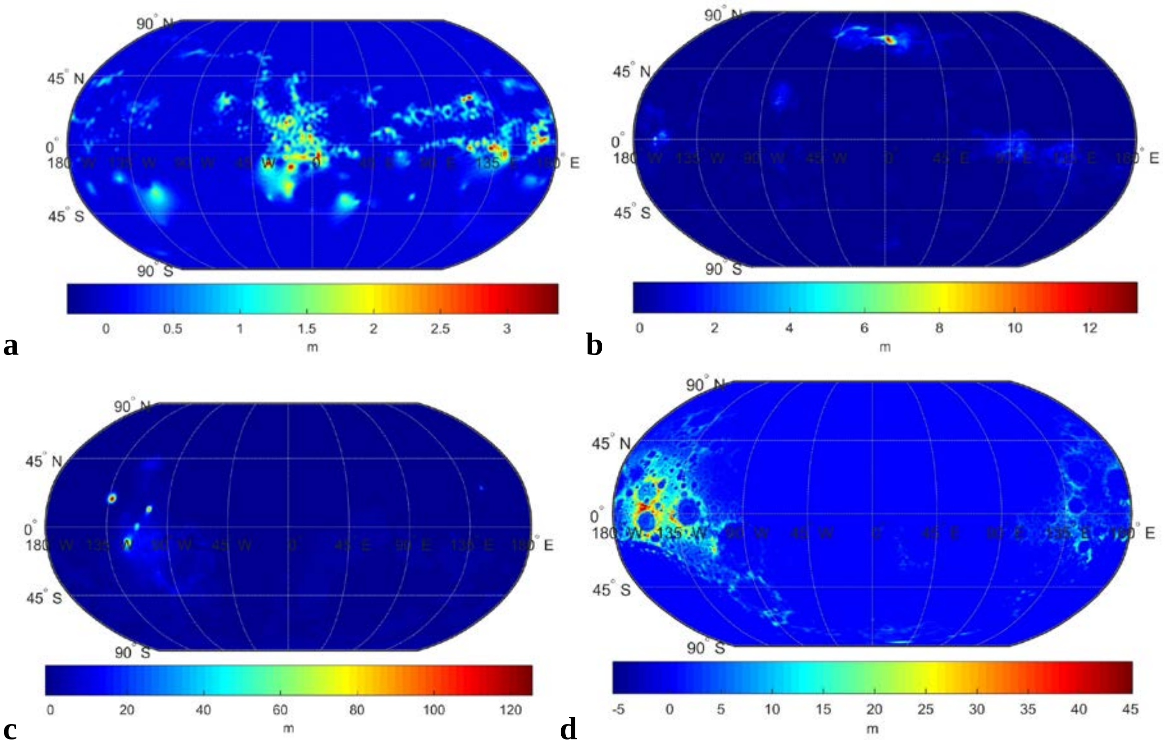
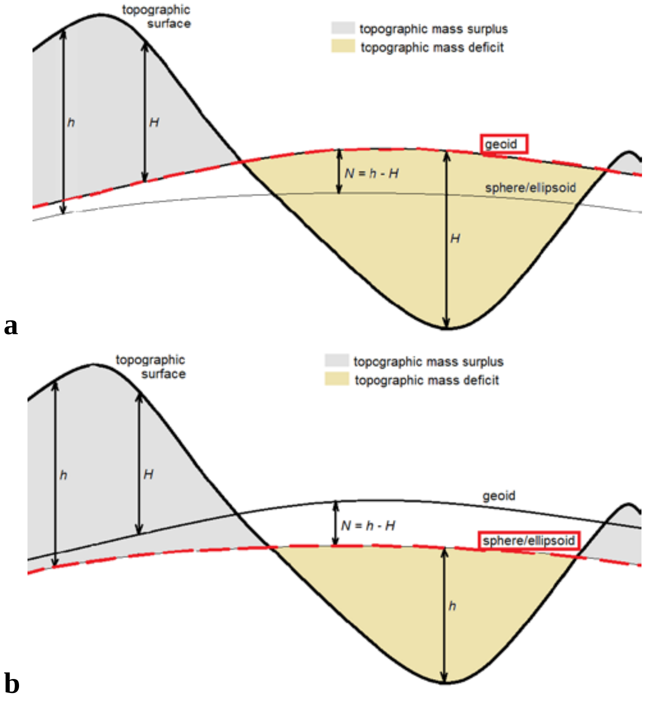


Figure 9: Differences between the accurate and approximate orthometric heights on (**a**) Mercury, (**b**) Venus, (**c**) Mars and (**d**) Earth's Moon.

In another theoretical study for planetary applications, Tenzer et al. (2019) proposed and examined numerically three possible schemes, see Fig. 10, how to compute the topographic gravity correction, and concluded that the optimal choice for computing the Bouguer gravity data, see Fig. 11, is based on the geoid-referenced surface.



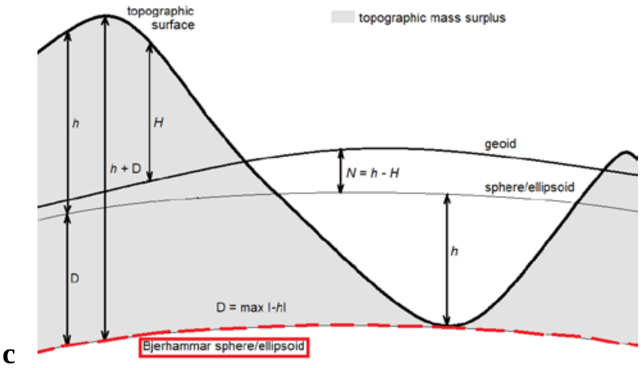


Figure 10: Possible scenarios of computing the topographic gravity correction for a height reference surface represented by (**a**) the geoid, (**b**) the geometric reference surface and (**c**) the Bjerhammar sphere/ellipsoid. Used notation: *h* the geometric height, *H* the physical height, *N* the geoidal height and *D* the (constant) depth of the Bjerhammar sphere/ellipsoid.

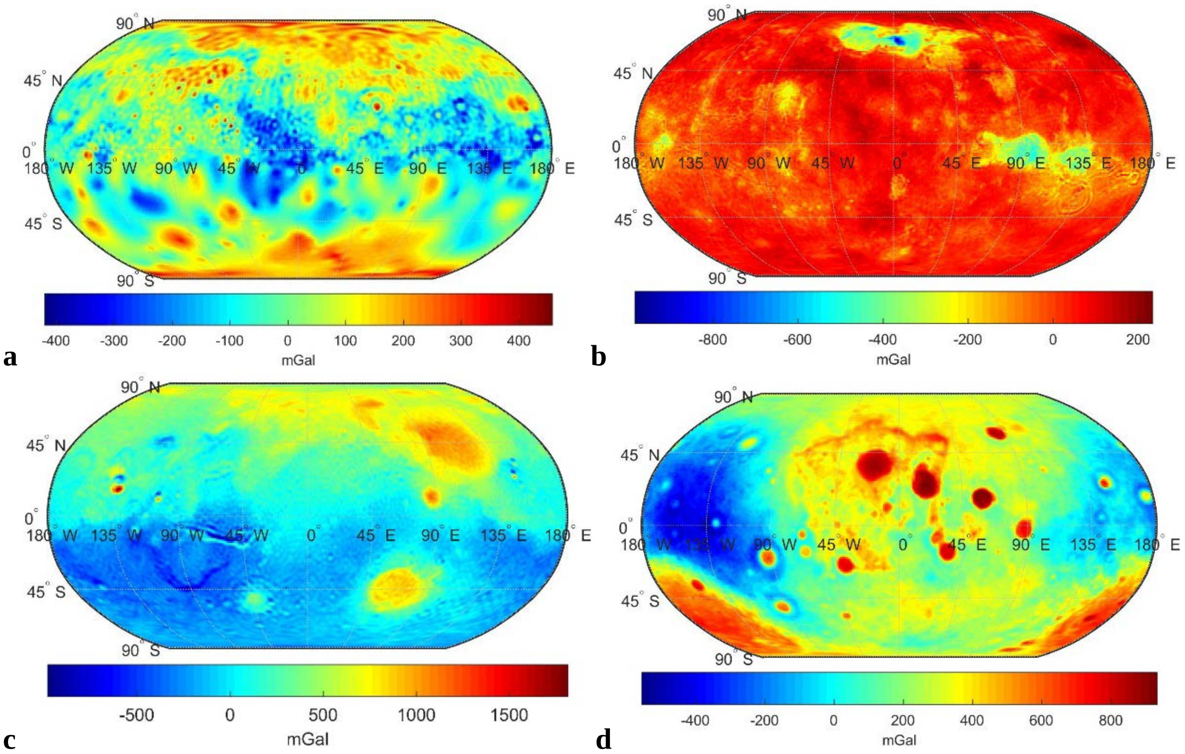


Figure 11: Bouguer gravity maps of (**a**) Mercury, (**b**) Venus, (**c**) Mars and (**d**) Earth's Moon computed for the geoid-referenced surface.

Gravity inversion techniques

Rossi et al. (2015) studied and implemented a Bayesian gravity inversion algorithm constrained on a-priori geological information. Reguzzoni et al. (2019) tested this approach below the Jiangmen Underground Neutrino Observatory (JUNO), currently under construction in the Guangdong Province (China). Since the geoneutrino signal measured by a liquid scintillator detector placed on the continental crust is dominated by the natural radioactivity of the closest geological units, they aimed at investigating the crustal structure that lies within ~300 km from the detector. The solution maximizing the posterior probability is the GIGJ (GOCE Inversion for Geoneutrinos at JUNO) crustal model for the Guangdong Province, see Fig. 12. The GIGJ model is consistent with the input geological and seismic information, and fits the GOCE gravity data with a standard deviation of 1 mGal. The model has been used to estimate the geoneutrino signal expected at JUNO and produced by unitary abundances of U and Th in the crustal layers.

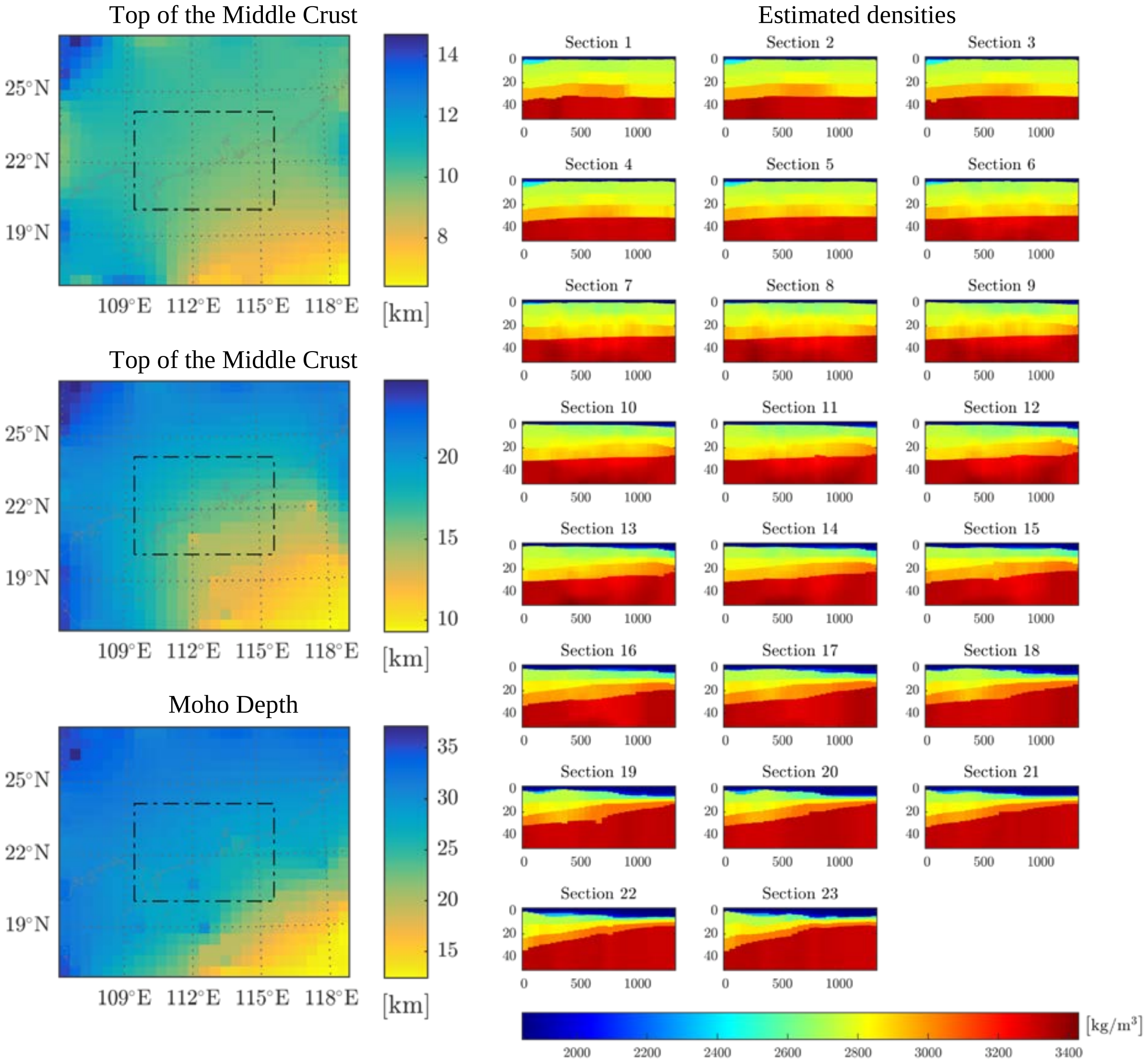


Figure 12: Estimated GIGJ model under the JUNO detector by the Bayesian inversion of GOCE data. Discontinuity surfaces on the left, density distribution on the right. Note that the top of the Upper Crust (i.e., the basement) is not estimated. Note also that the sections are numbered from North (1) to South (23), and cut the model from West to East.

Earth's core studies

Xin et al. (2015), Wang et al. (2015) and Wang and Song (2018) provided the evidence of equatorial anisotropy of Earth's inner-inner core.

1.3 Sessions organization at international congresses/symposia/workshops

Except for scientific activities, the members of JSG0.16 have been involved in organizing international conferences. R. Tenzer was the member of scientific committee of the 9th International Workshop on TibXS organized in Zhangye, China, August 6-10, 2018 and of the IX Hotine-Marussi Symposium in Rome, June 18-22, 2018. He is the IAG co-convener of the joint IAGA-IASPEI-IAG-ILP-IAVCEI session JA08: Probing the Earth's lithosphere and its dynamics using geophysical modelling at the IUGG General Assembly in Montreal, 8-18 July, 2019. L. Sjöberg and M. Bagherbandi are organizing the First International School on

Geoid Modelling, Gravity Inversion and its Application at the University of Gävle, Gävle, Sweden, 9-13 September, 2019.

1.4 Technology transfer and relevant applications in science and engineering

The proposed Bayesian algorithm (Rossi et al., 2015; Reguzzoni et al., 2019), which has been engineered into a set of software tools by a spin-off company of Politecnico di Milano, has been applied to oil exploration for scenarios with more than 1.5 million voxels and in presence of complex geological structures.

2. Future prospects

We expect to deliver the density model of the whole mantle based on the combined analysis of seismic and gravity data with additional geophysical and geochemical constraints that would serve as the Earth's synthetic model for testing numerical approaches for gravimetric forward and inverse modelling. This model will also serve to provide gravimetric images of the Earth's structure down to the core-mantle boundary zone. Special emphasis will be given to improve existing models of the asthenosphere and transition zone in the mantle.

2.1 Research

Gravimetric interpretation of the Earth's inner structure

- Spatial and spectral analysis of Earth's gravity field.
- Regional and continental-scale gravimetric studies of Antarctica, Indian Ocean, parts of Eurasia, South America and Africa.
- Studies of equatorial anisotropy of Earth's inner-inner core.
- Gravimetric studies of telluric planets and Earth's Moon.
- Compilation of Bouguer and mantle gravity maps of planets and moons.
- Studies of lithospheric stress field.

Numerical models

- Optimal numerical models for gravimetric forward and inverse modelling of lithospheric and deep mantle structures.

Density structure models

- Development and improvement of density model of Earth's lithosphere and asthenosphere.
- Compilation of new density model of continental sedimentary basins.

3. Publications

Members of JSG0.16 have extensively published their scientific results in peer-reviewed international journals. They also actively presented their results at major international conferences, such as IUGG 2015, ESA Living Planet 2016, IAG Gravity, Geoid and Height Systems 2016 Symposium, or the annual meetings organized by EGU and AGU. The members have usually participated and reported their results in sessions on gravity field modelling, lithospheric structure, solid Earth, planetary remote sensing, and vertical reference systems. The list of selected publications and presentations is below.

1. Abrehdary M, Sjöberg LE, Bagherbandi M (2016) The spherical terrain correction and its effect on the gravimetric-isostatic Moho determination. *Geophysical Journal International* 204(1): 262-273

2. Abrehdary M, Sjöberg LE, Bagherbandi M, Sampietro D (2017) Towards the Moho depth and Moho density contrast along with their uncertainties from seismic and satellite gravity observations. *Journal of Applied Geodesy*; https://doi.org/10.1515/jag-2017-0019.
3. Álvarez O, Gimenez M, Folguera A, Spagnotto S, Bustos E, Baez W, Braitenberg C (2015) New evidence about the subduction of the Copiapó ridge beneath South America, and its connection with the Chilean-Pampean flat slab, tracked by satellite GOCE and EGM2008 models. *Journal of Geodynamics* 91: 65-88
4. Bagherbandi M, Tenzer R, Abrehdary M, Sjöberg LE (2015) A New Fennoscandian crustal thickness model based on CRUST1.0 and gravimetric isostatic approach. *Earth-Science Review* 145: 132-145
5. Bagherbandi M, Sjöberg LE, Tenzer R, Abrehdary M (2015) On the rock equivalent topography effect in the gravimetric Moho determination. *Journal of Geodynamics* 83: 28-36
6. Bagherbandi M, Bai Y, Sjöberg LE, Abrehdary M, Tenzer R, Miranda S, Sanchez JMA (2017) Effect of the lithospheric thermal state on the Moho interface. *Journal of South American Earth Sciences* 76: 198-207
7. Bao X, Song X, Li J (2015) High-resolution lithospheric structure beneath Mainland China from ambient noise and earthquake surface-wave tomography. *Earth and Planetary Science Letters* 417:132-141
8. Bao X, Sun X, Xu M, Eaton DW, Song X, Wang L, Ding Z, Mi N, Li H, Yu D, Huang Z, Wang P (2015) Two crustal low-velocity channels beneath SE Tibet revealed by joint inversion of Rayleigh wave dispersion and receiver functions. *Earth and Planetary Science Letters* 415:16-24
9. Baranov A, Bagherbandi A, Tenzer R (2018) Combined gravimetric-seismic Moho model of Tibet. *Geosciences* 8(12): 461
10. Baranov A, Tenzer R, Bagherbandi M (2018) Combined gravimetric-seismic crustal model for Antarctica. *Surveys in Geophysics* 39(1): 23-56
11. Barzaghi R, Reguzzoni M, Borghi A, De Gaetani CI, Sampietro D, Marotta A (2015) Global to local Moho estimate based on GOCE geopotential models and local gravity data. *IAG Symposia Series* 142: 275-282
12. Braitenberg C, Sampietro D, Pivetta T, Zuliani D, Barbagallo A, Fabris P, Rossi L, Fabbri J, Mansi AH (2016) Gravity for detecting caves: airborne and terrestrial simulations based on a comprehensive karstic cave benchmark. *Pure and Applied Geophysics* 173(4):1243-1264
13. Braitenberg C, Pivetta T, Barbolla DF, Gabrovšek F, Devoti R, Nagy I (2019) Terrain uplift due to natural hydrologic overpressure in karstic conduits. *Scientific Reports* 9(1): 3934
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15. Chen W, Braitenberg C, Serpelloni E (2018) Interference of tectonic signals in subsurface hydrologic monitoring through gravity and GPS due to mountain building. *Global and Planetary Change* 167: 148-159
16. Chen W, Tenzer R (2015) Harmonic coefficients of the Earth's Spectral Crustal Model 180 - ESCM180. *Earth Science Informatics* 8(1): 147-159

17. Chen W, Tenzer R, Li H (2018) A regional gravimetric Moho recovery under Tibet using gravitational potential data from a satellite global model. *Studia Geophysica et Geodaetica* 62(4): 624-647
18. Chen W, Tenzer R (2017) Moho modelling in spatial domain: a case study under Tibet *Advances in Space Research* 59(12): 2855-2869
19. Chen W, Tenzer R (2017) Moho modelling using FFT technique. *Pure and Applied Geophysics* 174(4): 1743-1757
20. Chen W, Tenzer R (2019) Mantle and sub-lithosphere mantle gravity maps from the LITHO1.0 global lithospheric model. *Surveys in Geophysics* (submitted)
21. Chen L, Song X, Gerya TV, Xu T, Chen Y (2019) Crustal melting beneath orogenic plateaus: Insights from 3-D thermo-mechanical modeling. *Tectonophysics* 761: 1-15
22. Deng Y, Li J, Peng T, Ma Q, Song X, Sun X, Shen Y, Fan W (2019) Lithospheric structure in the Cathaysia block (South China) and its implication for the Late Mesozoic magmatism. *Physics of the Earth and Planetary Interiors* 291: 24-34
23. Deng Y, Li J, Song X, Li H, Xu T (2019) The lithospheric-scale deformation in NE Tibet from joint inversion of receiver function and surface wave dispersion. *Terrestrial, Atmospheric and Oceanic Sciences* 30 (1): 1-11
24. Deng Y, Li J, Song X, Zhu, L (2018) Joint Inversion for Lithospheric Structures: Implications for the Growth and Deformation in Northeastern Tibetan Plateau. *Geophysical Research Letters* 459: 3951-3958
25. Devoti R, Zuliani D, Braitenberg C, Fabris P, Grillo B (2015) Hydrologically induced slope deformations detected by GPS and clinometric surveys in the Cansiglio Plateau, southern Alps. *Earth and Planetary Science Letters* 419: 134-142
26. Du X, Song X, Zhang M, Lu Y, Lu Y, Chen P, Liu Z, Yang S (2015) Shale gas potential of the Lower Permian Gufeng Formation in the western area of the Lower Yangtze Platform, China. *Marine and Petroleum Geology* 67: 526-543
27. Eshagh M, Hussain M, Tenzer R, Romeshkani M (2016) Moho density contrast in central Eurasia from GOCE gravity gradients. *Remote Sensing – Remote Sensing in Tibet and Siberia* 8(5): 418
28. Eshagh M, Tenzer R (2015) Sub-crustal stress determined using gravity and crust structure models. *Computational Geosciences* 19(1): 115-125
29. Eshagh M, Tenzer R (2017) Lithospheric stress tensor from gravity and lithospheric structure models. *Pure and Applied Geophysics* 174(7), pp 2677-2688
30. Eshagh M, Ebadi S, Tenzer R (2017) Isostatic GOCE Moho model for Iran. *Journal of Asian Earth Sciences* 138: 12-24
31. Eshagh M, Steinberger B, Tenzer R, Tassara A (2017) Comparison of gravimetric and mantle flow solutions for sub-lithospheric stress modeling and their combination. *Geophysical Journal International* 213(2): 1013-1028
32. Eshagh M, Pitoňák M, Tenzer R (2018) Lithospheric elastic thickness estimates in central Eurasia. *Terrestrial, Atmospheric and Oceanic Sciences Journal* 30(1): 73-84
33. Hwang C, Shen WB, Shum CK, Song X (2019) Introduction to the special issue on Tibet: Contemporary geodetic-geophysical observations and interpretations. *Terrestrial, Atmospheric and Oceanic Sciences* 30(1): 1

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4.1 Presentations

Capponi M, Sampietro D, Reguzzoni M (2019) Earth crust regional modelling by Bayesian gravity inversion. Poster presentation at 3D Earth Science Meeting, 12-14 March 2019, Dublin, Ireland.

Mansi AH, Reguzzoni M, Sampietro D (2015) Modelling of subduction plates from GOCE gravity gradients along the satellite orbit. TopoEurope 2015, 4-7 October 2015, Antibes, France.

Marchetti P, Sampietro D, Capponi M, Rossi L, Reguzzoni M, Porzio F, Sansò F (2019) Lithological Constrained Gravity Inversion: A Bayesian Approach. Oral presentation at the 81st EAGE Conference and Exhibition, 3-6 June 2019, London, GB.

Reguzzoni M, Sampietro D (2019) The gravimetric contribution to the Moho estimation. Invited oral presentation at the International Conference: Earth's gravity field and Earth sciences, 22 March 2019, Accademia dei Lincei, Rome, Italy.

Rossi L, Reguzzoni M, Sampietro D (2015) Bayesian gravimetric inversion for local crustal model refinement in the Guangdong province, South China. EGU General Assembly 2015, 12-17 April 2015, Vienna, Austria.

Rossi L, Reguzzoni M, Sampietro D (2015) Guangdong province crustal modelling by applying a Bayesian inversion on a GOCE-based gravity model. TopoEurope 2015, 4-7 October 2015, Antibes, France.

Rossi L, Mansi AH, Reguzzoni M, Sampietro D (2017) Gravity inversion of the Kermadec-Tonga subduction zone by GOCE data and seismic information. EGU General Assembly 2017, 23-28 April 2017, Vienna, Austria.

Rossi L, Reguzzoni M, Baldoncini M, Callegari I, Poli P, Sampietro D, Strati V, Mantovani F (2018) GIGJ: a crustal model of the Guangdong Province using GOCE gravity data for predicting geoneutrinos. Oral presentation at EGU General Assembly 2018, 8-13 April 2018, Vienna, Austria.

Rossi L, Reguzzoni M, Sampietro D (2018) A parallel algorithm for the Bayesian gravity inversion. Poster presentation at the IX Hotine-Marussi Symposium, 18-22 June 2018, Rome, Italy.

Sampietro D, Mansi AH, Rossi L, Reguzzoni M (2016) Combining GOCE gravity gradients and seismic information to model subducting plates. Living Planet Symposium 2016, 9-13 May 2016, Prague, Czech Republic.

Sampietro D, Capponi M (2018) East Mediterranean Sea crustal structure from GOCE-based global gravity data. Poster presentation at MED 2018, 11-12 December 2018, ESA–ESRIN, Frascati, Rome, Italy.

Tenzer R, Zampa L, Eshagh M, Pitoňák M (2018) Origin of Venusian surface deformations from gravity and topographic models. The IX Hotine-Marussi International Symposium on Theoretical and Computational Geodesy, June 18-22, 2018, Rome, Italy (invited)

Tenzer R, Foroughi I, Sjöberg LE, Bagherbandi M, Hirt C, Pitoňák M (2018) Theoretical and practical aspects of defining the heights for planets and moons. Session 7: Theoretical aspects of height system realization, The IX Hotine-Marussi International Symposium on Theoretical and Computational Geodesy, June 18-22, 2018, Rome, Italy

Tenzer R (2018) Lithospheric Structure of West Antarctic Rift Zone. SE28-A055: General Contributions in Solid Earth. Asia Oceania Geosciences Society (AOGS), 15th Annual Meeting, June 3-8, 2018, Honolulu, Hawaii

Tenzer R, Pitoňák M, Foroughi I (2018) Physical Heights for Telluric Planets. PS09-A034: Science and Exploration of Mars and Venus. Asia Oceania Geosciences Society (AOGS), 15th Annual Meeting, June 3-8, 2018, Honolulu, Hawaii

Tenzer R, Foroughi I (2017) Height systems for planets. International Symposium on Planetary Remote Sensing and Mapping, Hong Kong, 13-16 August, 2017

Tondi R, Borghi A, Reguzzoni M, Vuan A, Klin P (2015) Gravity data for a 3-D density model of the Po plain and the surrounding region. EGU General Assembly 2015, 12-17 April 2015, Vienna, Austria.

Joint Study Group 0.17: Multi-GNSS theory and algorithms

Chair: *Amir Khodabandeh (Australia)*
Affiliation: *Commissions 1, 4 and GGOS*

Members

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1. Activities

1.1 Summary

This report presents an overview of activities undertaken towards the objectives of the JSG 0.17 since 2015. The aim of the study group is to identify and investigate challenges posed by processing/integrating data of the next generation satellite navigation systems, developing optimal methods capable of multi-GNSS data processing, thereby articulating new algorithms and findings through journals, conferences and group discussions.

We had a group discussion on the inter-system-biases (ISBs). The ISBs pop up in the multi-GNSS measurement setup, because the receiver instrumental delays are experienced in a way that is ‘different’ from system to system (the term ‘system’ refers to a satellite constellation). The members were invited to give their opinions about 1) significance, 2) estimation and 3) outlook of the ISBs for multi-GNSS positioning and non-positioning applications. A few members contributed to the discussion and provided their feedback. A summary is given as follows. A conservative way of dealing with the ISBs is to treat them as unknown and estimate them on the fly, often without any temporal constraints. Although this approach leads to a slightly weaker solution, but then one does not have to worry about any unit-specific bias that would not be properly accounted for by calibration values or by possible intra-day variations due to, e.g., temperature changes. In this perspective, the benefits of calibrating ISBs and the potential applications are limited to controlled environments where equipment (receiver type and firmware version) are well defined. On the other hand, there are methods that offer ISBs calibration. In particular, for networks of a large number of receivers, a-priori ISBs calibration enables one to take a common pivot satellite among multiple systems, thus considerably increasing the GNSS network model’s redundancy. The outlook would be that as part of the IGS analysis centers’ work, all receiver manufacturers will be aligned to employ the same standards, presenting receiver instrumental delays with no ISBs. Several scenarios on properly handling the ISB parameters in the GNSS network models are presented in (Khodabandeh and Teunissen 2016a).

1.2 Research

Undifferenced, uncombined multi-frequency formulation: Most of the current methods for GNSS data processing are based on forming combined observations (e.g., ionosphere-free, wide-lane and Melbourne-Wubbena combinations). These methods are therefore restrictive in the light of the development of new multi-frequency GNSS constellations. Odijk et al. (2015)

presented an undifferenced, uncombined multi-frequency formulation of the GNSS observation equations and showed how one should interpret *estimable* forms of the GNSS parameters. They further applied their method to integer ambiguity resolution-enabled precise point positioning (PPP-RTK) and presented the positioning performance improvements that can be expected by multi-GNSS PPP-RTK setup. Further results on mutli-GNSS positioning are provided in (Odolinski and Khodabandeh 2016). As to the non-positioning applications, Khodabandeh and Teunissen (2016b) applied the method to the GNSS array model and analysed the estimability and precision of multi-frequency GNSS-derived slant Total Electron Content (TEC), showing that the variance of the TEC solutions follows the 1-over-n (1-over-f) rule and decreases the more the number of antennas/frequencies (n: number of array antennas, f: number of frequencies).

The advent of multi-GNSS mass-market receivers: A vast number of low-cost receivers, tracking satellites of multiple systems, have entered the market. Odolinski and Teunissen (2017a, b) showed, in contrast to their single-GNSS counterparts, that these receivers can offer high-precision positioning if one rigorously integrates their multi-GNSS data, see also the smartphone implementation of such receivers (Odolinski and Teunissen 2018).

The triple-frequency BeiDou signals: Following the study on the stochastic model of triple-frequency BeiDou signals (Li 2016), (Li et al. 2017) investigated the RTK performance of the extra-wide-lane observations available through the BeiDou triple frequencies. Given fast successful ambiguity resolution, the extra-wide-lane observations were shown to provide RTK solutions with a horizontal accuracy of 10 cm.

GLONASS FDMA signals: Banville (2016) presented a strategy for long-baseline ambiguity resolution applicable to the GLONASS L1/L2 FDMA signals. Benefiting from the frequency-spacing of the signals, ionosphere-free ambiguities were defined, improving the repeatability of static PPP solutions by more than 20 %, see also (Banville et al. 2018).

GLONASS CDMA signals: Zaminpardaz et al. (2017) presented world-first results of the GLONASS L3 signals. They studied the noise characteristics, the integer ambiguity resolution performance, and the positioning performance. In particular, the GLONASS data were shown to have a lower noise level than that of GPS, particularly in case of the code data.

Integrity monitoring: Teunissen (2017) presented a new distributional theory for the combination of testing and estimation with applications to GNSS integrity, see also (Imparato et al. 2018) and (Zaminpardaz et al. 2018 and 2019).

Distributed estimation and filtering for GNSS: Khodabandeh et al. (2018) applied a consensus-based distributed Kalman filter to a network of GNSS receivers. It was shown how single-receiver, but collaborative, GNSS users can achieve high-precision solutions without the need of relying on centralized computing centers, see (Khodabandeh and Teunissen 2019).

1.3 Sessions organization at international congresses/symposia/workshops

- Organization of the session Theory of multi-GNSS parameter estimation (A. Khodabandeh, M. Crespi) at the IX Hotine-Marussi Symposium (Rome, Italy) in 2018.

1.4 Editorial activity

- Guest editors of Special issue (2019) in Journal of Spatial Science of "Multi-GNSS processing, positioning and applications", open for submissions until 1 May (R. Odolinski, P.J.G. Teunissen, B. Zhang).

2. Future prospects

Integration of multiple navigation satellite systems (multi-GNSS) will be a vital part of low-cost GNSS RTK receivers. Morevover, design and development of low-cost antennas, mitigating the impact of multipath, would benefit low-cost multi-GNSS receivers.

The following areas need addressing in the coming period:

- GNSS integrity: development of proper theory as current theory is still not adequate.
- Mass-market dense networks: with the combination of multi-GNSS (=lot of satellites) and low-cost receivers (=having many receivers becomes affordable) real advantage should be taken of the much denser sampling of the atmosphere.
- Computational efficiency of estimation and testing: with the huge increase of GNSS data real challenges exits to perform rigorous testing and estimation efficiently.
- Determination of the stochastic model of low-cost multi-frequency and multi-GNSS equipment. This includes estimation of temporal-and cross-correlation of multi-GNSS measurements as well as other probabilistic parameters like measumement distributions.
- Characterization of the inter-system, inter-/intra-frequency biases and inter-satellite-type-biases for low-cost mass-market receivers.

3. Selected publications

1. Banville S, Collins P, Lahaye F (2018) Model comparison for GLONASS RTK with low-cost receivers. *GPS Solution* 22: 52, https://doi.org/10.1007/s10291-018-0712-3.
2. Laurichesse D, Banville S (2018) Instantaneous centimeter-level multi-frequency precise point positioning. *GPS World*, July 2018.
3. Banville S (2016) GLONASS ionosphere-free ambiguity resolution for precise point positioning. *Journal of Geodesy* 90: 487; doi:10.1007/s00190-016-0888-7.
4. Giorgi G (2016) Attitude determination. In: *Encyclopedia of Geodesy*. Edited by EW Grafarend, Earth Sciences Series, Springer; doi: 10.1007/978-3-319-02370-0_2-1.
5. Imparato D, Teunissen PJG, Tiberius CCJM (2018) Minimal detectable and identifiable biases for quality control. *Survey Review*. https://doi.org/10.1080/00396265.2018.1437947
6. Khodabandeh A, Teunissen PJG (2019) Distributed least-squares estimation applied to GNSS networks (*invited paper*), Measurement Science and Technology, Special issue of *High-Precision Multi-Constellation GNSS: Methods, Selected Applications and Challenges* (Editors: J. Paziewski and M. Crespi); doi: https://doi.org/10.1088/1361-6501/ab034e.
7. Khodabandeh A, Teunissen PJG, Zaminpardaz A (2018) Consensus-based distributed filtering for GNSS. Chapter in *Kalman Filters-Theory for Advanced Applications*, 273-304; doi: 10.5772/intechopen.71138
8. Khodabandeh A, Teunissen PJG (2016a) PPP-RTK and inter-system biases: the ISB look-up table as a means to support multi-system PPP-RTK. *Journal of Geodesy* 90(9): 837-851
9. Khodabandeh A, Teunissen PJG (2016b) Array-aided multifrequency GNSS ionospheric sensing: estimability and precision analysis. *IEEE Transactions on Geoscience and Remote Sensing* 54(10): 5895–5913
10. Li B, Li Z, Zhang Z, Tan Y (2017) ERTK: Extra-wide-lane RTK of triple-frequency GNSS signals. *Journal of Geodesy*; doi:10.1007/s00190-017-1006-1.

11. Li B, Zhang L, Verhagen S (2016) Impacts of BeiDou stochastic model on reliability: overall test, w-test and minimal detectable bias. *GPS Solutions*; doi: 10.1007/s10291-016-0596-z.
12. Li H, Li B, Lou L, Yang L, Wang J (2016) Impact of GPS differential code bias in dual- and triple-frequency positioning and satellite clock estimation. *GPS Solutions*; doi: 10.1007/s10291-016-0578-1.
13. Li B (2016) Stochastic modeling of triple-frequency BeiDou signals: estimation, assessment and impact analysis. *Journal of Geodesy* 90: 593-610
14. Nardo A, Li B, Teunissen PJG (2016) Partial ambiguity resolution for ground and space-based applications in a multi-GNSS scenario: a simulation study. *Advances in Space Research* 57(1): 30-45
15. Li B, Feng Y, Gao W, Li Z (2015) Real-time kinematic positioning over long baselines using triple-frequency BeiDou signals. *IEEE Transactions on Aerospace and Electronic Systems* 51(4): 3254-3269
16. Odijk D, Khodabandeh A, Nadarajah N, Choudhury M, Zhang B, Li W, Teunissen PJG (2016) PPP-RTK by means of S-system theory: Australian network and user demonstration, *Journal of Spatial Science*; doi:10.1080/14498596.2016.1261373
17. Odijk D, Zhang B, Khodabandeh A, Odolinski R, Teunissen PJG (2015) On the estimability of parameters in undifferenced, uncombined GNSS network and PPP-RTK user models by means of S-system theory. *Journal of Geodesy* 90(1): 15-44
18. Odolinski R, Teunissen PJG (2018) An assessment of smartphone and low-cost multi-GNSS single-frequency RTK positioning for low, medium and high ionospheric disturbance periods. *Journal of Geodesy*; doi: 10.1007/s00190-018-1192-5.
19. Odolinski R, Khodabandeh A (2016) Multi-GNSS positioning. In EW Grafarend (Ed.), *Encyclopedia of Geodesy*; Springer; doi: 10.1007/978-3-319-02370-0_142-1.
20. Odolinski R, Teunissen PJG (2017a) Low-cost, high-precision, single-frequency GPS–BDS RTK positioning. *GPS Solutions*; doi: 10.1007/s10291-017-0613-x.
21. Odolinski R, Teunissen PJG (2017b). On the performance of a low-cost single-frequency GPS+BDS RTK positioning model. In: Proceedings of Institute of Navigation (ION) International Technical Meeting (ITM), Monterey, California, USA.
22. Teunissen PJG (2017) Distributional theory for the DIA method. *Journal of Geodesy* 92(1): 59–80
23. Zaminpardaz S, Teunissen PJG, Nadarajah N (2017) GLONASS CDMA L3 ambiguity resolution and positioning. *GPS Solutions*; doi: 10.1007/s10291-016-0544-y.
24. Zaminpardaz S, Teunissen PJG (2018) DIA-datasnooping and identifiability. *Journal of Geodesy* 93 (1): 85-101; https://doi.org/10.1007/s00190-018-1141-3.
25. Zaminpardaz S, Teunissen PJG, Tiberius CJM (2019) Risking to underestimate the integrity risk. *GPS Solutions* 23; https://doi.org/10.1007/s10291-018-0812-0.

Joint Study Group 0.18: High resolution harmonic analysis and synthesis of potential fields

Chair: *Sten Claessens (Australia)*
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Kurt Seitz (Germany)

1. Activities

1.1 Summary

The gravitational fields of the Earth and other celestial bodies in the Solar System are customarily represented by a series of spherical, spheroidal or ellipsoidal harmonic coefficients. The maximum degree and order (d/o) of harmonic series of the Earth's gravitational potential has risen steadily over the past decades. This has posed and continues to pose both theoretical and practical challenges for the geodetic community. Members of this study group have achieved progress on several of these challenges.

The computation of associated Legendre functions (ALFs) of the first kind, which are required for spherical harmonic analysis and synthesis, has traditionally been subject to numerical instabilities and underflow/overflow problems. These problems have successfully been solved, and efficient, stable and accurate computation of ALFs of extremely high d/o is now possible thanks to new algorithms. Progress has also been made on spherical harmonic analysis given a number of different functionals on various surfaces. Software for ultra-high degree harmonic analysis and synthesis has been developed and made publicly available.

Ultra-high degree models (up to d/o ~46,000) of topography and its constituents and of topographic potential have been generated using improved techniques. This shows a clear advance over earlier models, and it has led to new insights. One example is the improved understanding of the correlation between gravitational and topographic potential at small spatial scales.

The divergence of harmonic series inside the Brillouin surface has been shown to be a significant challenge for ultra-high degree harmonic models. For example, traditional spherical harmonic series of the Earth's gravitational potential start to diverge at the Earth's surface at degrees that are now achievable, and for other celestial bodies divergence has been observed at much lower degrees. Some advances have been made on dealing with this challenge, but further research is required.

1.2 Research

Algorithms and software for ultra-high degree spherical and spheroidal harmonic analysis and synthesis

- Algorithms for precise and stable computation of associated Legendre functions of the first and second kind (or ratios thereof), plus its derivatives and integrals [10, 12, 13, 14 and 18].
- Software development for ultra-high degree surface harmonic analysis and synthesis [6] [13, 14, 28 and 29].
- Algorithms for harmonic analysis using input data of various types and on various surfaces [8, 9, 11, 19, 25, 35 and 36].

Convergence vs divergence in spherical and spheroidal harmonic series

- Convergence/divergence of spherical harmonic synthesis on the Earth’s surface [21].
- Divergence effect and amplified omission errors on the Moon and other celestial bodies [5, 23 and 26].

High-resolution spherical and spheroidal models and degree variance models

- High-resolution harmonic models of topography and its constituents [20 and 29].
- High-resolution harmonic models of topographic or topographic-isostatic potential fields and their computation [1, 2, 3, 15, 16, 17, 31, 32 and 33].
- High-resolution harmonic models of the global or local gravitational potential field [4, 22 and 30].

Applications of high-resolution harmonic models

- Computation of spherical harmonic Bouguer gravity anomalies [21].
- Correlation between gravitational and topographic potential [24].
- The spectral filter problem in residual terrain modelling [34].

1.3 Sessions organisation at international congresses/symposia/workshops

- Organisation of the session *Global gravity modelling and height systems (D. Tsoulis, S. Claessens)* at the IX Hotine-Marussi Symposium (Rome, Italy) in 2018.
- Organisation of the session *Theory and methods of potential fields (D. Tsoulis, S. Claessens, M. Fedi)* at the IUGG General Assembly (Montreal, Canada) in 2019.

1.4 Technology transfer and relevant applications in science and engineering

- High-resolution harmonic models of the gravitational and topographic potential fields of the Earth and other celestial bodies are made available via the website of the International Centre for Global Earth Models (ICGEM) (http://icgem.gfz-potsdam.de/tom_reltopo).
- Software for high-degree harmonic analysis and synthesis has been developed and made available. This includes updates to the MATLAB-based GrafLab and isGrafLab software for spherical harmonic synthesis, new MATLAB-based code for ultra-high degree surface spherical harmonic analysis (http://edisk.cvt.stuba.sk/~xbuchab/) [6], an extension to the open-source SHTools software for use to ultra-high degree (https://www.researchgate.net/publication/291102839_ultra_high_degree_extension_v1_SHTOOLS) [29], development of routines for efficient computation of ultra-high degree associated Legendre functions [13 and 14].

2. Cooperation/Interactions with IAG Commissions and GGOS

Commission 2

- SC 2.2: Methodology for Geoid and Physical Height Systems – Chair J. Ågren (Sweden)

GGOS

- Focus Area Unified Height Systems – Chair: Laura Sánchez (Germany)

3. Future prospects

3.1 Research

Algorithms and software for ultra-high degree spherical and spheroidal harmonic analysis and synthesis

- Study efficient methods for ultra-high degree and order harmonic analysis and synthesis for all potential quantities of interest on regular and irregular boundary surfaces.
- Comparison between least-squares and quadrature approaches to ultra-high d/o spherical and spheroidal harmonic analysis.
- Continued development of software for ultra-high degree surface harmonic analysis and synthesis, including inter-comparison between different software packages.

Convergence vs divergence in spherical and spheroidal harmonic series

- Comparison of traditional and Runge-Krarup-type spherical and spheroidal harmonic series on the surface of the Earth and other celestial bodies.

High-resolution spherical and spheroidal models and degree variance models.

- Continued algorithm improvement for computation of high-resolution harmonic models of topography and its constituents, topographic or topographic-isostatic potential fields, and gravitational potential fields based on the latest input data.

3.2 Technology transfer and relevant applications in science and engineering

- Aim to have all ultra-high degree harmonic models made available in one location.
- Provide a repository for freely accessible software for high-degree harmonic analysis and synthesis.

4. Publications

1. Abd-Elmotaal H, Kühtreiber N (2015) On the computation of the ultra-high harmonic coefficients of the topographic-isostatic masses within the data window. General Assembly of the European Geosciences Union (EGU), Vienna, Austria, April 12-17

2. Abd-Elmotaal H, Kühtreiber N (2019) Alternative approach for the determination of the austrian gravimetric geoid. General Assembly of the European Geosciences Union (EGU), Vienna, Austria, April 7-12

3. Abd-Elmotaal H, Kühtreiber N (2019) One-step rigorous algorithm for the harmonic analysis of topographic-isostatic masses on the ellipsoid with bench-marking approach. *Survey Review* (in press).

4. Bucha B, Janák J, Papčo J, Bezděk A (2016) High-resolution regional gravity field modelling in a mountainous area from terrestrial gravity data. *Geophysical Journal International* 207: 949-966

5. Bucha B, Hirt C, Kuhn M (2019) Divergence-free spherical harmonic gravity field modelling based on the Runge-Krarup theorem: a case study for the Moon. *Journal of Geodesy* 93: 489-513

6. Bucha B, Hirt C, Kuhn M (2019) Cap integration in spectral gravity forward modelling: near- and far-zone gravity effects via Molodensky's truncation coefficients. *Journal of Geodesy*, 93: 65-83

7. Bucha B, Hirt C, Kuhn M (submitted) Cap integration in spectral gravity forward modelling up to the full gravity tensor. *Journal of Geodesy*.
8. Claessens SJ, Hirt C (2015) A surface spherical harmonic expansion of gravity anomalies on the ellipsoid. *Journal of Geodesy* 89(10): 1035-1048
9. Claessens SJ, (2016) Spherical harmonic analysis of a harmonic function given on a spheroid. *Geophysical Journal International* 2016(1): 142-151
10. Fukushima T (2015) Numerical computation of point values, derivatives, and integrals of associated Legendre function of the first kind and point values and derivatives of oblate spheroidal harmonics of the second kind of high degree and order. *IAG Symposia Series* 143:192-197
11. Fukushima T (2016) Zonal toroidal harmonic expansions of external gravitational fields for ring-like objects. *The Astronomical Journal* 152: 35
12. Fukushima T (2017) Rectangular rotation of spherical harmonic expansion of arbitrary high degree and order. *Journal of Geodesy* 91(8): 995-1011
13. Fukushima T (2018) Transformation from surface spherical harmonic expansion of arbitrary high degree and order to double Fourier series on sphere. *Journal of Geodesy* 92(2): 123-130
14. Fukushima T (2018) Fast computation of sine/cosine series coefficients of associated Legendre function of arbitrary high degree and order. *Journal of Geodetic Science* 8(1): 162-173.
15. Grombein T, Seitz K, Heck B (2016) The Rock–Water–Ice topographic gravity field model RWI_TOPO_2015 and its comparison to a conventional rock-equivalent version. *Surveys in Geophysics* 37(5): 937-976
16. Grombein T, Seitz K, Heck B (2017) On high-frequency topography-implied gravity signals for height system unification using GOCE-based global geopotential models. *Surveys in Geophysics* 38(2): 443-477
17. Grombein T (2017) Gravity forward modelling with a tesseroid-based Rock-Water-Ice approach – theory and applications in the context of the GOCE mission and height system unification. PhD thesis, Schriftenreihe des Studiengangs Geodäsie und Geoinformatik, Karlsruhe Institute of Technology (KIT), KIT Scientific Publishing, Karlsruhe, Germany
18. Gruber C, Abrykosov O (2016) On computation and use of Fourier coefficients for associated Legendre Functions. *Journal of Geodesy* 90: 525-535
19. Hamáčková E, Šprlák M, Pitoňák M, Novák P (2016) Non-singular expressions for the spherical harmonic synthesis of gravitational curvatures in a local north-oriented reference frame. *Computers and Geosciences* 88: 152-162
20. Hirt C, Rexer M (2015) Earth2014: 1 arc-min shape, topography, bedrock and ice-sheet models – available as gridded data and degree-10,800 spherical harmonics. *International Journal of Applied Earth Observation and Geoinformation* 39: 103-112
21. Hirt C, Reußner E, Rexer M, Kuhn M (2016) Topographic gravity modelling for global Bouguer maps to degree 2,160: Validation of spectral and spatial domain forward modelling techniques at the 10 microgal level. *Journal of Geophysical Research – Solid Earth* 121(9): 6846–6862
22. Hirt C, Rexer M, Scheinert M, Pail R, Claessens S, Holmes S (2016) A new degree-2190 (10 km resolution) gravity field model for Antarctica developed from GRACE, GOCE and Bedmap2 data. *Journal of Geodesy* 90(2): 105-127

23. Hirt C, Kuhn M (2017) Convergence and divergence in spherical harmonic series of the gravitational field generated by high-resolution planetary topography – a case study for the Moon. *Journal of Geophysical Research – Planets* 122(8): 1727-1746
24. Hirt C, Rexer M, Claessens S, Rummel R (2017) The relation between degree-2160 spectral models of Earth’s gravitational and topographic potential – a guide on global correlation measures and their dependency on approximation effects. *Journal of Geodesy* 91(10): 1179-1205
25. Holota P, Nesvadba O (2015) Fundamental solution of Laplace's equation in oblate spheroidal coordinates and Galerkin's matrix for Neumann's problem in Earth's gravity field studies. General Assembly of the European Geosciences Union (EGU), Vienna, Austria, April 12-17.
26. Hu X, Jekeli C (2015) A numerical comparison of spherical, spheroidal and ellipsoidal harmonic gravitational field models for small non-spherical bodies: examples for the Martian moons. *Journal of Geodesy* 89(2): 159-177
27. Jekeli C (2017) *Spectral methods in geodesy and geophysics*. CRC Press, Boca Raton, Florida, USA, 430 pp.
28. Nesvadba O, Holota P (2015) An OpenCL Implementation of Ellipsoidal Harmonics. In: Sneeuw N., Novák P., Crespi M., Sansò F. (eds) VIII Hotine-Marussi Symposium on Mathematical Geodesy. *IAG Symposia Series* 142, Springer.
29. Rexer M, Hirt C (2015) Ultra-high degree surface spherical harmonic analysis using the Gauss-Legendre and the Driscoll/Healy quadrature theorem and application to planetary topography models of Earth, Moon and Mars. *Surveys in Geophysics* 36(6): 803-830
30. Rexer M, Hirt C (2015) Spectral analysis of the Earth's topographic potential via 2D-DFT – a new data-based degree variance model to degree 90,000. *Journal of Geodesy* 89(9): 887-909
31. Rexer M, Hirt C, Claessens SJ, Tenzer R (2016) Layer-based modelling of the Earth's gravitational potential up to 10km-scale in spherical harmonics in spherical and ellipsoidal approximation. *Surveys in Geophysics* 37(6): 1035-1074
32. Rexer M (2017) Spectral Solutions to the topographic potential in the context of high-resolution global gravity field modelling. Successfully defended PhD thesis, TUM Ingenieurfakultät Bau Geo Umwelt, TU Munich, 212 pp.
33. Rexer M, Hirt C, Pail R (2017) High-resolution global forward modelling – A degree-5480 global ellipsoidal topographic potential model. Poster EGU2017-7725 presented at EGU General Assembly, European Geosciences, Vienna, Austria, 23-28 April
34. Rexer M, Hirt C, Bucha B, Holmes S (2018) Solution to the spectral filter problem of residual terrain modelling (RTM). *Journal of Geodesy* 92: 675-690
35. Sebera J, Bezděk A, Kostelecký J, Pešek I, Shum CK (2016) An oblate ellipsoidal approach to update a high-resolution geopotential model over the oceans: Study case of EGM2008 and DTU10. *Advances in Space Research* 57(1): 2-18
36. Sebera J, Bezděk A, Pešek I, Henych T (2016) Spheroidal models of the exterior gravitational field of Asteroids Bennu and Castalia. *Icarus* 272: 70-79

Joint Study Group JSG 0.19: Time series analysis in geodesy

Chair: *Wiesław Kosek (Poland)*
Affiliation: *Commissions 1, 3, 4 and GGOS*

Members

Michael Schmidt (Germany)
Jan Vondrák (Czech Republic)
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1. Activities

1.1 Summary

Different deterministic and stochastic time series analysis methods were used to analyze geodetic time series such as Earth Orientation Parameters (EOP) and their fluid excitation functions, permanent station positions, geocenter coordinates, altimetric sea level anomaly (SLA) data and troposhperic parameters. Special emphasis has been placed on detection of non-linear motion and noise character in GNSS station positions time series in order to determine of their reliable velocities. In some papers the spatio-temporal filtering of GNSS station position time series has been proposed to examined common seasonal time-varying signals as well as the impact of environmental loadings on these station position time series has been taken into account. In same papers different EOP forecast methods are discussed.

1.2 Research

The combination of the Fourier Transform Band Pass Filter with the Hilbert transform (FTBPF+HT) was applied to compute variable amplitudes and phases of seasonal and subseasonal oscillations in altimetric SLA data (Kosek et al. 2015a). Normalized Morlet wavelet transform (NMWT) of the differences between pole coordinates data and their predictions computed by combination of the least-squares and autoregressive (AR) forecasts revealed residual prograde Chandler and annual oscillations (Brzezinski et al. 2016). The wavelet based semblance filtering (Kosek et al. 2015b) and the FTBPF+HT methods were used to detect systematic errors in geocenter coordinates determined from GNSS, SLR, DORIS, and GRACE (Kosek et al. 2019).

The problem of least squares function fitting using the orthogonal system of trigonometric functions for the observation model comprising complex-valued deterministic function observations in equidistant time moments was considered by Popiński (2016), where the observed function values are corrupted by multiplicative errors in amplitude and phase as well as additive noise. Theoretical and numerical aspects of adaptive decomposition of square integrable band-limited functions into a finite number of additive components using the FTBPF concept was investigated by Popiński (2018).

The Prognocean Plus system has been developed to predict altimetric SLA data in real time using three deterministic-stochastic data-based models and the results were compared with the MyOcean system and the previous version of Prognocean (Świerczyńska et al. 2016). To modelling long-term sea level variation due to changes of ocean floor the new method for reconstructing the ocean depth-age curve has been proposed with comparable accuracy to already existing models (Niedzielski et al. 2016) and the novel approach to estimate the reference ocean depth has been developed (Jurecka et al. 2016). The overview of different prediction methods in marine studies has been published by Niedzielski (2017).

The short-term 5-hour forecasts of Zenith Total Delay (ZTD) time series were computed by the AR and autoregressive moving average (ARMA) models to provide fully operational service for real-time PPP (Precise Point Positioning) (Wilgan 2015).

Analyses of seasonal signals in the GNSS coordinate time series using the iterative Least Squares Estimation approach (iLSE) together with estimation of correlation between these coordinates and deformations of the Earth's crust have been presented by Kaczmarek and Kontny (2018a). The methods of identifying the noise model in the GNSS station coordinates time series using Continuous Wavelet Transform (CWT) coefficients for signal reconstruction and the least squares estimation signal for annual and semi-annual period revealed flicker noise in these series (Kaczmarek and Kontny 2018b).

A non-parametric wavelet decomposition was employed to investigate the non-linear motion of GNSS stations (Bogusz 2015). The velocities with associated uncertainties of GPS position time series of 115 European stations were estimated by noise analysis to include the power-law dependencies in uncertainties' estimates and it showed that these time series are characterized by the power-law noise close to flicker noise with amplitudes reaching 20 mm/yr-κ/4 at maximum (Klos and Bogusz 2017). Rescaled-range method with Hurst exponent and detrended fluctuation analysis were used to analyze 130 Polish GPS position time series and results proved that there is a clear dependence between consecutive values of GPS residuals, indicating a power-law noise presence (Bogusz et al. 2016a). Similarly, to the daily GPS position time series (Klos et al. 2016a), the weekly-sampled data are characterized by power-law noise, shown by Klos et al. (2015); however, due to their sparser sampling, the amplitudes of weekly observations are smaller than for the daily time series. The impact that the pre-analysis has on the noise estimates, has been demonstrated by Klos et al. (2016b) for the outliers. The authors focused on various methods to identify and remove values outlying from others, followed by noise analysis and they concluded that the outliers have to be identified and removed to provide the best estimates of noise character. Bogusz et al. (2016b) described the methodology of reliable determination of the velocities of permanent GNSS stations. They showed, that proper treatment of either deterministic or stochastic part of the position time series will lead to the most reliable velocities along with their uncertainties. Klos et al. (2018e) provided a General Dilution of Precision (GDP) estimates, being the ratio of two uncertainties of velocities. Both uncertainties are determined from two different deterministic models while accounting for stochastic noise at the same time. The authors proved that adding more and more seasonal terms to the series, we increase the bias of the velocity uncertainties. They estimated that 9 and 17 years of continuous daily observations is needed for, respectively, flicker and random-walk noise to make the GDP decrease below 5%. Klos et al. (2018a) focused on the estimates of noise character in DORIS position time series and it was noticed, that this character changed thorough years from autoregressive process into pure power-law noise, with the quality of data significantly improved. Bogusz and Klos

(2016) analyzed another part of the functional model of the GNSS position time series. Seasonal signatures were modelled using tropical, Chandler, and draconitic periods, all from 1st to 9th harmonics. This approach was compared to the frequently employed assumptions that the tropical signal is modelled using annual and semi-annual-only curves. It was stated that the new approach helps to improve the velocity uncertainty of 56% at maximum. Bogusz et al. (2015a) applied the wavelet decomposition using Meyer's symmetric wavelet to reliably describe the changes in seasonal amplitudes in 3D GNSS position times series derived by the JPL. Gruszczynska et al. (2016, 2018) proposed to use the Singular Spectrum Analysis (SSA) with its multivariate variant (MSSA) to described this year-to-year variability. Gruszczynska et al. (2017) examined common seasonal time-varying signal for a set of European stations using Multichannel Singular Spectrum Analysis (MSSA) and proved that common seasonal curves are better-fitted to the original series than the Least-Squares estimates and the MSSA approach leads to no reduction in the time series power, which constitutes another advantage of this methodology. Klos et al. (2018c) proposed a two-stage method to subtract the impact of the environmental (atmosphere, non-tidal part of ocean changes and terrestrial hydrosphere) loadings on the GNSS position time series. They proved, that previous attempts to reliably remove loading impact failed by changing the stochastic part significantly along with uncertainties of the permanent station velocity. Application of the Improved SSA (ISSA) solved this problem, which was demonstrated on the vertical position changes of 376 permanent IGS stations, derived as the official contribution to International Terrestrial Reference Frame (ITRF2014). Klos et al. (2018b) noticed that wavelet decomposition, Chebyshev polynomials, SSA or Kalman filtering, do all influence the stochastic part of the GNSS position time series, once the seasonal part was modelled and removed, i.e. the stochastic part of seasonal signal is also removed. This will falsify the results of the noise analysis, and also, the velocity estimates and their uncertainties. Klos et al. (2019) introduced new methodology named as the Adaptive Wiener Filter (AWF) to estimate the time-varying seasonal signals including the character of the original time series. The AWF has been confronted with the commonly employed Kalman Filter, Singular Spectrum Analysis, Wavelet Decomposition and Least-Squares methods, demonstrating that it provides the accurate estimates for time-varying seasonalities, leaving the noise character intact. Bogusz et al. (2015b) used a 5-year daily GPS position time series time series (2008-2012) in the ITRF2008 processed at the Military University of Technology to evaluate the Common-Mode Error (CME), defined as the superposition of the technique-dependent and environmental systematic errors present in the them. Gruszczynski et al. (2016) proposed to use orthogonal transformation to subtract CME. They studied the Principal Component Analysis (PCA) with the existence of a non-uniform spatial response in the network to the CME being assumed. They found an improvement (by means of better credibility) of accuracy of the determined velocity being accompanied by the spatio-temporal filtering of position time series. Gruszczynski et al. (2018) introduced the probabilistic PCA (pPCA) which allows the spatio-temporal filtering to estimate and subtract the CME, with no need to interpolate the missing values. The efficiency of the proposed algorithm was firstly tested on the simulated incomplete time series, then the CME was estimated for a set of 25 permanent stations situated in central Europe. They found, that more than 36% of the total variance represented by the time series residuals can be explained by the 1st Principal Component (PC). Since the other PCs variances turned out to be less than 8%, they concluded that that common signals stored in the 1st PC are significant in GNSS residuals. The Zenith Wet Delay (ZWD) tropospheric series character examined by Klos et al. (2018d). showed that the first-order autoregressive noise process combined along with white noise is preferred over the widely employed white-noise-only approach and it was found that the ZWD trend uncertainty is largely underestimated (by 5–14 times) using the white-noise-only assumption.

A summary of research activities concerning theoretical geodesy performed during 2011-2014 and 2015-2019 in Poland were presented by Borkowski and Kosek (2015) and Borkowski et al. (2019), respectively.

Hourly time series of Earth rotation parameters from VLBI observations in a single-session strategy were determined. Then, the S1 (period of 24h) amplitudes for these time series were determined. First, the sine- and cosine-amplitudes were fitted with a classical least-squares approach, and, as an alternative approach, the so-called "stacked" day was generated, which was then used to derive the amplitudes (Girdiuk et al. 2016).

Estimation of the free core nutation (FCN) period is a challenging prospect, due to the non-stationary characteristics of celestial pole offsets (CPO). Instead of the direct Fourier Transform (FT) approach, the FCN period is estimated by another direct method, i.e, the sliding-window complex least-squares fit method (SCLF). The estimated uncertainty of the FCN period falls from several tens of days to several days from the FT to the SCLF method, which suggests that the SCLF method may serve as an independent direct way to estimate the FCN period (Zhou et al. 2016).

The study (Xu and Zhou 2015) firstly employs the calculation of base sequence with different length, in 1–90 day predictions of EOP, by the combined method of least squares and autoregressive model, and find the base sequence with best result for different prediction spans, which we call as "predictions over optimized data intervals". Compared to the EOP predictions with fixed base data intervals, the "predictions over optimized data intervals" performs better for the EOP prediction, and particularly promotes our competitive level in the international activity of EOP Combination of Prediction Pilot Project.

Artificial neural networks and fuzzy inference systems to predict the polar motion starting from daily to up to 1 year in future were applied. Such methods are capable to learn the nonlinear behaviour of the polar motion and use it successfully for prediction (Kucak et al. 2016).

Wu et al. (2015) used a Kalman filter to determine terrestrial reference frames from time series of the positions of stations in geodetic networks, the associated EOPs, and ground survey measurements.

Least-squares model of the deformation of the sea floor caused by an earthquake was fitted to the time series of GPS site displacement and oceanic tsunami measurements (Fu et al. 2017).

The period and Q of the Chandler wobble are estimated by finding those values that minimize the power in the Chandler frequency band of the difference between observed and modeled polar motion excitation functions. The observations of the polar motion excitation functions that we used are derived from both space-geodetic polar motion observations and from satellite laser ranging (SLR) and Gravity Recovery and Climate Experiment (GRACE) observations of the degree-2 coefficients of the Earth's time-varying gravitational field (Nastula and Gross 2015).

The problem of detecting discontinuities is fundamental for reliably estimating velocities from GNSS station position time series. Discontinuities may be related to equipment changes, earthquakes or ununderstood causes. In Gazeaux et al. (2015), GNSS position time series of a group of nearby stations are automatically assessed for discontinuity detection using an advanced mathematic method based on dynamic programming. It allows simultaneously estimating station-specific trends, seasonal signals and a common ground motion signal between all series as well as individual offsets in all time series. Bertin et al. (2017) have worked on a similar model but by investigating offsets at a station by station basis. A dictionary of function has been proposed to model station displacements as well as station discontinuities.

The time-variable Earth gravity field harmonics from the GRACE satellite mission are used to determine seasonal and nonseasonal scales of polar motion excitation functions from global geophysical fluids, and particularly from the portion from land-based hydrology. Hydrological excitation functions of polar motion from the mass of equivalent water thicknesses (EWT) derived gravimetrically from the solutions of three GRACE processing centers, the Center for Space Research (CSR), JPL and the GeoforschungsZentrum (GFZ), are intercompared. Additionally, we estimate the hydrological signal as well in a different manner, as a residual from geodetically observed polar motion, by subtracting atmospheric (pressure + wind) and oceanic (bottom pressure + currents) contributions (Nastula et al. 2016).

In the paper by Van Camp et al. (2016a) we revealed from continuous gravity measurements the evapotranspiration of a forested ecosystem at the mesoscale (~50 ha), by stacking hourly values. In the paper by Van Camp et al. (2016b) we showed that 7 calibrations of a superconducting gravimeter (SG) using an absolute gravimeter (each during a few day) are needed to ensure calibration of the SG at the 1 per mille level with 99% confidence. This was achieved through LSQ analysis and bootstrapping. The attenuation bias is discussed as well (case of noisy x and y time series in the LSQ process). Van Camp et al. (2016c) using Allan deviation analysed the signature of climate-induced interannual mass transfers on repeated absolute gravity measurements, everywhere in the world.

Meurers et al. (2016) revealed statistically significant temporal variations of M2 tidal parameters. This requires performing tidal analysis, which consist in LSQ adjustment of observed tides vs. predicted ones by ephemeris.

At JPL a sequential estimation approach to determining terrestrial and celestial reference frames using either a Kalman filter or a square-root information filter were developed (Abbondanza et al. 2017, 2019, Soja et al. 2018a,b, Wu et al. 2015). Three-corner hat method was applied to estimate uncertainties of station position measurements (Abbondanza et al. 2015). A Kalman filter was developed to smooth and predict celestial pole offsets (Nastula et al. 2019).

1.3 Sessions organization at international congresses/symposia/workshops

- Organization of the session Multi-sensor and time series data analysis (W. Kosek, K. Sosnica) at the IX Hotine-Marussi Symposium (Rome, Italy) in 2018.
- Co-organization of the PICO sessions "Mathematical methods for the analysis of potential field data and geodetic time series" at the European Geosciences Union General Assemblies in 2015, 2016, 2017, 2018 and 2019 in Vienna, Austria.

2. Cooperation/Interactions with IAG Commissions and GGOS (500 characters)

Commission 3
- SC 3.1: Earth Tides and Geodynamics – Chair: J. Bogusz (Poland),
- SC 3.3: Earth Rotation and Geophysical Fluids – Chair: J. Chen (USA)

Commission 4
- SC 4.3: Atmosphere Remote Sensing – Chair: Michael Schmidt (Germany)

3. Future prospects

3.1 Research

Permanent station position problems

- Detection of reliable station velocities and their uncertainties with taking into account their non-linear motion and environmental loadings.
- Application of different spatio-temporal methods to identify clusters with similar velocities of permanent station coordinates.

Earth Orientation Parameters
- Better short term prediction using the fluid excitation functions.

Sea level anomalies
- Optimal filtering and prediction for climate variability research.

Troposphere and Ionosphere parameters
- Deterministic and stochastic modelling and prediction for real time applications, e.g., precise GNSS positioning.

3.2 Sessions organization at international congresses/symposia/workshops

- Organization of a session on time series analysis in geodesy at the *X Hotine-Marussi Symposium* in 2022.
- Co-organization of the PICO sessions "Mathematical methods for the analysis of potential field data and geodetic time series" at the European Geosciences Union General Assemblies in Vienna, Austria.

3.3 Editorial activity

- JSG publications: review papers on time series analysis in geodesy co-authored by the JSG 0.19 Members.

3.4 Technology transfer and relevant applications in science and engineering

- Reference bibliography in time series analysis in geodesy.

4. Publications

1. Abbondanza C, Altamimi Z, Chin TM, Gross RS, Heflin MB, Parker JW, Wu X (2015) Three-Corner Hat for the assessment of the uncertainty of nonlinear residuals of space-geodetic time series in the context of terrestrial reference frame analysis. *Journal of Geodesy* 89(4): 313-329, doi: 10.1007/s0010-014-0777-x.

2. Abbondanza C, Chin TN, Gross RS, Heflin MB, Parker JW, Soja BS, van Dam T, Wu X (2017) JTRF2014, the JPL Kalman filter and smoother realization of the International Terrestrial Reference System. *Journal of Geophysical Research* 122(10): 8474-8510, doi: 10.1002/ 2017JB014360.

3. Abbondanza C, Chin TM, Gross RS, Heflin MB, Parker JW, Soja BS, Wu X (2019) A sequential estimation approach to terrestrial reference frame determination. *Comptes Rendus Geoscience,* submitted.

4. Bertin K, Collilieux X, Lebarbier E, Meza C (2017) Semi-parametric segmentation of multiple series using a DP-Lasso strategy. *Journal of Statistical Computation and Simulation* 87(6): 1255-1268, doi: 10.1080/00949655.2016.1260726.

5. Bogusz J (2015). Geodetic aspects of GPS permanent stations non-linearity studies. *Acta Geodynamica et Geomaterialia* 12(4): 323-333, doi: 10.13168/AGG.2015.0033.

6. Bogusz J, Gruszczynska M, Klos A, Gruszczynski M (2015a) Non-parametric estimation of seasonal variations in GPS-derived time series. *IAG Symposia Series* 146: 227-233, doi: 10.1007/1345_2015_191.
7. Bogusz J, Gruszczynski M, Figurski M, Klos A (2015b) Spatio-temporal filtering for determination of common mode error in regional GNSS networks. *Central European Journal of Geosciences* 7: 140-148, doi: 10.1515/geo-2015-0021.
8. Bogusz J, Klos A (2016) On the significance of periodic signals in noise analysis of GPS station coordinates time series. *GPS Solutions* 20(4): 655-664, doi: 10.1007/s10291-015-0478-9.
9. Bogusz J, Klos A, Figurski M, Kujawa M (2016a) Investigation of long-range dependencies in daily GPS solutions. *Survey Review* 48(347): 140-147, doi: 10.1179/ 1752270615Y.0000000022.
10. Bogusz J, Klos A, Gruszczynska M, Gruszczynski M (2016b) Towards reliable velocities of permanent GNSS stations. *Reports on Geodesy and Geoinformatics* 100(1): 17-26, doi: 10.1515/rgg-2016-0003.
11. Borkowski A, Kosek W (2015) Theoretical geodesy. *Geodesy and Cartography* 64(2): 261-27
12. Borkowski A, Kosek W (2015). Theoretical geodesy. *Geodesy and Cartography* 64: 99-113, doi: 10.1515/geocart-2015-015.
13. Borkowski A, Kosek W, Ligas M (2019) General theory and methodology 2015-2018. *Geodesy and Cartography* 68(1), accepted.
14. Brzeziński A, Józwik M, Kaczorowski M, Kalarus M, Kasza D, Kosek W, Nastula J, Szczerbowski Z, Wińska M, Wronowski R, Zdunek R, Zieliński JB (2016) Geodynamic research at the Department of Planetary Geodesy, SRC PAS. *Reports on Geodesy and Geoinformatics* 100/2016: 131-147, doi: 10.1515/rgg-2016-0011.
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Joint Study Group 0.20: Space Weather and Ionosphere

Chair: *Klaus Börger (Germany)*
Affiliation: *Commissions 1, 4 and GGOS*

Members

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Andreas Goss (Germany)
Johannes Hinrichs (Germany)
Anno Löcher (Germany)
Niclas Mrotzek (Germany)
Michael Schmidt (Germany)
Kristin Vielberg (Germany)

1. Activities

1.1 Summary

The principal goal of the Joint Study Group 0.20 was to investigate effects of an extreme and severe space weather event – referred to as Carrington event – on geodetic techniques or, in an extended view, on technical systems and applications such as navigation, satellites, communication and so on. In detail, we specified six tasks, i.e. to analyse (1) the impact of an extreme solar event on satellite motion, (2) the impact of an extreme solar event on GNSS (especially navigation), (3) the impact of an extreme solar event on signal propagation w.r.t. communication-techniques, (4) the impact of an extreme solar event on re-entry computations, (5) the impact of an extreme solar event on the life-time of space debris and (6) the impact of an extreme solar event on the International Space Station (ISS).

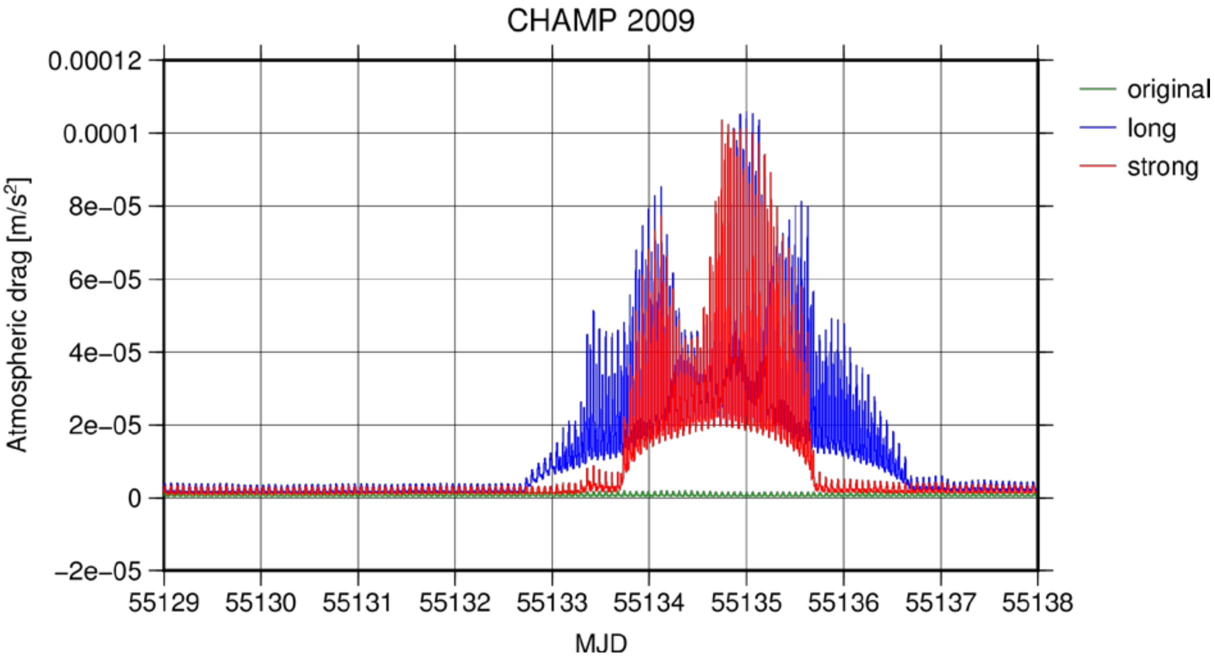

Figure 1: Simulated atmospheric drag for a LEO-satellite (called CHAMP) at 300 km altitude.

1.2 Achieved results

At the very beginning, the Joint Study Group designed and agreed upon a **work program**. This work program describes all necessary steps, the relations between the single work packages, a responsible person for the respective milestones and a time schedule. Afterwards, the program was to put into practice. We installed a **website** to provide information to interested people and – being more important – to serve as a platform for an internal exchange of news as well as of data and results.

Members of the Joint Study Group firstly worked on the **characterization of a superstorm**. At a first glance, this seems to be an easy matter, but it is far from trivial, since we had to consider very complex relationships. Therefore, a thorough analysis of previous (extreme) solar events was necessary to find regularities and to transfer a Carrington-event in our time. Eventually we took the Halloween-event of 2003 as a template and then we mainly introduced two changes. We amplified the storm and additionally we extended storm-duration. Further, we did not only consider the year 2003, but we moved the event also into the year 2009, being a period of low solar activity.

Finally, we had three different types of data for two different years, in each case denoted as ORIGINAL, STRONG and LONG. In terms of content, the simulation affects Kp-values, the F10.7 radio flux – both provided in standard formats, which is WDC for the Kp-value and which is FLUXTABLE.TXT for F10.7 – and the ionosphere. Concerning the latter, it is quite difficult to model an ionosphere that matches the situation described by the specified Kp-values and the specified values for the F10.7 radio flux. We put a lot of work into the principal component analysis (PCA) of the ionosphere, but in the end, the results were not satisfactory. For example, the correlations between the principal components and the time series of the physical parameters (Kp, F10.7 and others) were too weak, and in general, the percentages of the modes were too low.

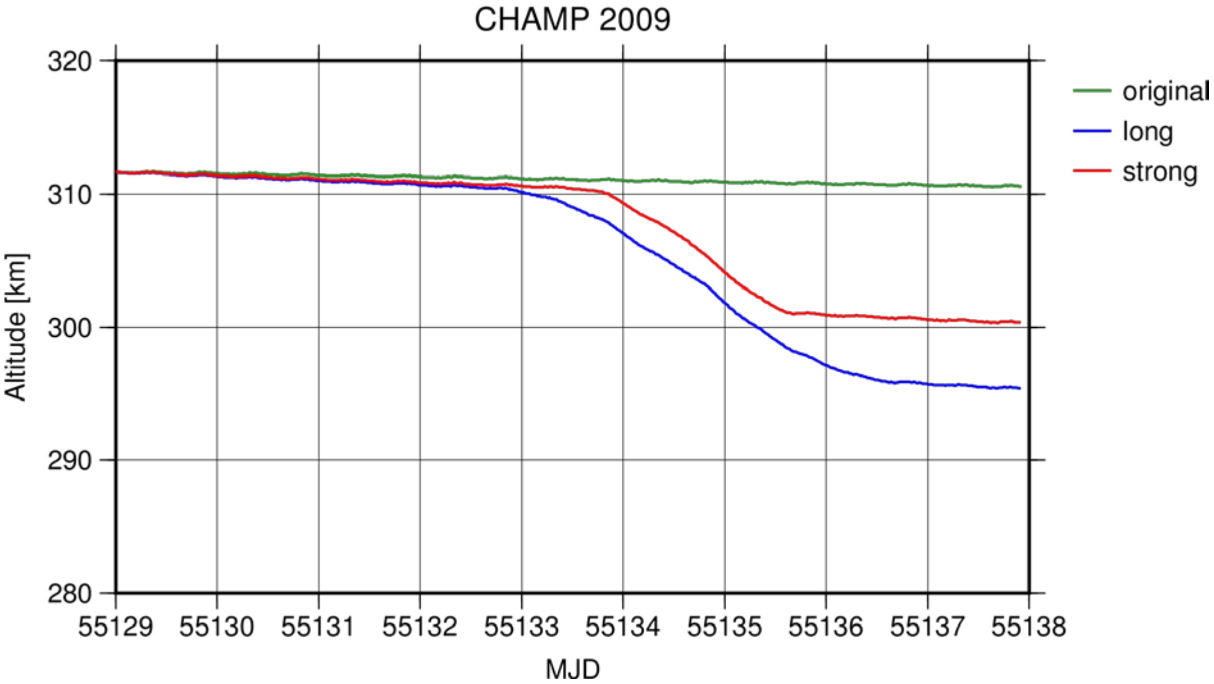

Figure 2: Loss of altitude of a LEO-satellite (called CHAMP).

As mentioned in the introduction, the Joint Study Group investigated different **effects of a solar superstorm**. The influence on satellite motion is particularly spectacular and shortly presented in the following for the year 2009. We used the corresponding simulation data and evaluated atmospheric drag, shown in Fig. 1, for a LEO-satellite (called CHAMP) at an altitude of about 300 km. The rising of the force is extraordinary, i.e. about two orders of magnitude, and it causes an enormous orbital decay, shown in Fig. 2. The decay is 12 km for the STRONG-variant and 17 km for the LONG-variant. The decay rate for both is 5 km per day. We made the same computations for the ISS, revealing a dramatic loss of altitude, which is about 30 km. Overall, the studies of the Joint Study Group 0.20 show in terms of amount, that a solar superstorm would have significant effects on space debris, the ISS, satellite motion and satellite orientation.

1.3 Final remarks

The Joint Study Group has done important and valuable work on space weather research. All findings were presented at the Hotine-Marussi Symposium 2018 in Rome. Concerning the ionosphere, further research has to be done to analyse spatial structures and the temporal behaviour. Then, the outcome can be used to model an ionospheric superstorm.

Joint Study Group 0.21: Geophysical modelling of time variations in deformation and gravity

Chair: *Yoshiyuki Tanaka (Japan)*
Affiliation: *Commissions 2 and 3*

Members

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Riccardo Riva (Netherlands)
Wouter van der Wal (Netherlands)
Peter Vajda (Slovak Republic)
Jose Fernandez (Spain)
Benjamin Fong Chao (Taiwan)
David Al-Attar (UK)
Pablo J. Gonzalez (UK)
Erik Ivins (USA)

1. Activities

1.1 Summary

Improving observational accuracy of the GNSS and the GRACE has promoted our understanding of regional to global scale surface crustal deformations and mass redistributions associated with atmosphere, ocean, ice sheets, continental water and great earthqukes. In addition to those observations, InSAR and terrestrial gravity measurements have allowed us to elucidate local deformations due to earthquakes, volcanos, groundwater and landslides. The purpose of our group is to detect and model deformation and gravity change caused by such phenomena based on geodetic and geophysical data. Selected results during 2015-2019 are highlighted below.

Extensive studies were carried out to reconstruct regional glacial isostatic adjustment (GIA) and hydrological processes. It was discovered that the GIA, Greenland ice mass loss and mantle convection are the substantial three sources which drive the long-term polar drift since AD 1900. In those studies dealing with elastic and viscoelastic responses to surface loads, more and more theoretical models have been proposed which consider 3D heterogeneities and nonlinear rheologies. Benchmark tests between different codes have also been conducted for solving sea-level equations, indicating the validity of the adopted numerical approaches for modeling and understanding the GIA. Some studies incoporated thermal effects into the GIA models with use of geophysical data. Inversion methods were also developed which enable efficient computations.

A deep structure of the Earth was also studied. A large-scale density anomaly in the lowermost mantle was constrained from observations of body tides. A 6-year variation in the length-of-day was found, relating to the inner-core libration, which in turn creates a 6-year westward propagating wave. This wave is manifested in the GNSS, geomagnetic and global gravity data.

In the modeling of local deformations, new physical mechanisms were proposed in addition to elastic/viscoelastic deformaton, such as viscoplastic deformation, thermal pressurization, poroelastic deformation, erosion and detachment. Earthquake cycle mechanically driven by slab pull was presented, instead of kinematically imposed fault slip.

1.2 Research

Earthquake, volcano and landslide

- Earthquake-induced local crustal deformation [13, 14, 60, 81 and 82]
- Viscoelastic relaxation due to great earthquake
- GNSS and GRACE data analysis and interpretation [16, 26, 35, 50 and 101]
- Sea-level rise due to postseismic relaxation [53]
- Modeling of far-field deformation detected by GNSS [67 and 110]
- Modeling of lateral heterogeneity in viscosity [98]
- Forward and inverse modelling in a heterogeneous spherical Earth with nonlinear rheologies [27]
- Poroelastic deformation
    - Near-surface fluid injection [89]
    - Gravity change due to deep fluid flow triggered by slow slip [99]
- Earthquake cycle deformation, non-kinematically driven by slab pull [47]
- Volcano gravimetry and related theories [55, 80, 105, 106, 111 and 112]
- Volcanic crustal deformation modeling [10, 15, 21, 29, 37, 38, 44 and 104],
- including thermochemical effects [36] and hydrothermal pressurization [45]
- Landslide modeling based on GNSS and InSAR data [11, 17 and 40]
- 3D viscoplastic finite element method [18]
- Data analysis techniques by InSAR and GNSS [8 and 71]
- Review for modeling and data analysis [46]

Plate tectonics

- Relative plate motion of Iberian Peninsula [79]
- Seismotectonics in Himalaya [33]
- Recent surface vertical displacements of the European Alps and the possible mechanisms including geological effects [93]
- Regional GNSS observation network [39]
- Moho depth determination using gravity data [9]

Surface mass variations

- Reviews on theory and applications of satellite missions [59, 92, 77 and 103]
- Atmospheric and hydrological mass variations
    - Surface mass variations and crustal deformations from GNSS and GRACE data [42, 43, 51, 52, 75 and 102]
    - Effects of Lateral heterogeneity on the elastic response [30 and 100]
    - A numerical global deformational model for use with elastic responses [1]
- Glacial Isostatic Adjustment (GIA)
    - Regional models [3, 34, 54, 57, 58, 62, 83, 84, 86, 88, 90, 91, 97, 107 and 109]
    - Vertical motion and sea level change [5, 49, 61, 65, 66 and 85]

- Deformation due to sediment transport [108]
- Mantle-plume driven thermomechanical ice sheet model [87]
- Effects of viscous heating on surface heat flow [56]
- Inversion methods and sensitivity analyses for 1D and 3D earth parameters [22, 28, 48, 68 and 76]
- Benchmark tests for sea-level equations [69]

Tides and Earth rotation

- The 20th Century polar motion and its sources [2, 4 and 23]
- Effects of earthquakes on polar motion [20 and 25]
- Estimation and interpretation of low-degree coefficients [73, 94, 95 and 96]
- A generalized normal mode theory for the tidal response [63]
- Body tide observations to constrain lateral variations in density in the lowermost mantle [64]
- Lower mantle viscosity and anelasticity inferred from geodetic data [31 and 74]
- 6-year variation in the length-of-day relating to the inner-core libration, consistent with geodetic and geomagnetic data [32]
- Effects of boundary topography on free oscillation seismology, body tides, and rotational dynamics [7]
- Importance of proper implementation of rotation variations in GIA modelling derived from the energy balance approach [78]

1.3 Sessions organization at international congresses/symposia/workshops

- Organization of “Interrelation between seismicity and gravity field anomalies – New insights into earthquake rupture processes” at *the AGU fall meeting* in 2016.
- Organization of IAG Workshop on GIA and Elastic Deformation (Reykjavik, Iceland) in 2017 (http://www.polar.dtu.dk/english/Workshop-on-Glacial-isostatic-adjustment-and-elastic-deformation-2017).
- Organization of the sessions on GIA at *the EGU General Assemblies* in 2017 and 2018 and *the AGU Fall Meeting* in 2017.
- Field work on Etna in 2018 (http://www.geo.sav.sk/en/slovak-italian-volcano-gravimetric-campaign-etna-2018/).
- Co-organization of the session “Deformation and gravity field modelling at regional scales” at *the IX Hotine-Marussi Symposium* (Rome, Italy) in 2018.

1.4 Editorial activity

- Fernández J, Pepe A, Sigmundsson F, Poland M (2017) *Journal of Volcanology and Geothermal Research*. Special Issue: “Measuring Changes at Volcanoes using Geodesy: an update of Methods and Results”, 344, 1-288.

1.5 Technology transfer and relevant applications in science and engineering

- Melini et al. (2015) developed a new tool for the computation of the Earth’s response to surface loads (REAR).
- Bevis et al. (2016) reviewed methods to compute the geoelastic response to a disk load and provided a MATLAB function to implement this alhgorithm.
- Gao et al. (2017) opened a code for calculating viscoelastic postseismic deformation in a spherically symmetric, self-gravitating layered Earth.
- Camacho et al. (2018) presented a software package to carry out inversions of surface deformation data (any combination of InSAR, GPS, and terrestrial data, e.g., EDM,

levelling) as produced by 3D free-geometry extended bodies with anomalous pressure changes.

2. Cooperation/Interactions with IAG Commissions and GGOS

Commission 2
- SC 2.3: Satellite Gravity Missions – Chair: Adrian Jäggi (Switzerland)
- SC 2.6: Gravity and Mass Transport in Earth System – Chair: Jürgen Kusche (Germany)

Commission 3
- SC 3.1: Earth Tides and Geodynamics – Chair: J. Bogusz (Poland)
- SC 3.2: Crustal Deformation – Chair: Z.-K. Shen (China)
- SC 3.3: Earth Rotation and Geophysical Fluids – Chair: J. Chen (USA)
- SC 3.4: Cryospheric Deformation – Chair: S. Abbas Khan (Denmark)
- SC 3.5: Tectonics and Earthquake Geodesy – Chair: H. Ozener (Turkey)

3. Future prospects

3.1 Research

Constraint of 3D heterogeneities in density and viscoelastic structure
- Model developments which consider 3D heterogeneities and nonlinear rheology.
- Sensitivity analyses and inversion methods to make use of observation data.
- Integration of geophysical data such as seismic tomography, heat flow, high-temperature/high-pressure experiments and geomagnetic data.
- Elucidation of the cause of the 6-year variation in the LOD.

Exploration and application of new model factors to local deformations
- Thermochemical structure, hydrothermal pressurization, plastic deformation and poroelastic deformation due to crustal fluid flow.
- Dynamic plate subduction model for understanding earthquake cycles where slip is not imposed in advance.
- Benchmark tests for postseismic viscoelastic deformation in a self-gravitating/non-gravitating, flat/spherical, 3D/1D Earth models.

3.2 Sessions organization at international congresses/symposia/workshops

- Organization of a session on deformation and gravity variation at the *X Hotine-Marussi Symposium* in 2022.
- Co-organization of sessions on GIA at *EGU General Assembly/AGU fall meeting.*
- Proposal for a theoretical session on deformation and gravity variation at those meetings.

3.3 Technology transfer and relevant applications in science and engineering

- Reference bibliography for deformation and gravity variation.
- Distribution code which computes postseismic viscoelastic deformation in a 3D heterogeneous, self-gravitating spherical Earth.

4. Publications

1. Adhikari S, Ivins ER, Larour E (2016) ISSM-SESAW v1.0: mesh-based computation of gravitationally consistent sea level and geodetic signatures caused by cryosphere and

climate driven mass change. *Geosci. Model Dev.* 9: 1087-1109; doi: 10.5194/gmd-9-1087-2016.

2. Adhikari S, Ivins ER (2016) Climate-driven polar motion: 2003–2015. *Science Adv.* 2 (4): e1501693; doi: 10.1126/sciadv.1501693.
3. Adhikari S, Ivins ER, Larour E (2017) Mass transport waves amplified by intense Greenland melt and detected in solid Earth deformation. *Geophysical Research Letters* 44; doi: 10.1002/2017GL073478.
4. Adhikari S, Caron L, Steinberger B, Reager JT, Kjeldsen KK, Marzeion B, Larour L, Ivins ER (2018) What drives 20th Century polar motion? *Earth Planet Sci. Lett.* 502: 126-132, https://doi.org/10.1016/j.epsl.2018.08.059.
5. Adhikari S, Ivins ER, Frederikse T, Landerer FW, Caron L (2019) Sea-level fingerprints emergent from GRACE mission data. *Earth Syst. Sci. Data Discuss.*, https://doi.org/10.5194/essd-2019-3, (in press).
6. Al-Attar D, Crawford O (2016) Particle relabelling transformations in elastodynamics, *Geophysical Journal International* 205: 575–593
7. Al-Attar D, Crawford O, Valentine, AP, Trampert, J (2018) Hamilton’s principle and normal mode coupling in an aspherical planet with a fluid core. *Geophysical Journal International* 214: 485-507
8. Alinia, H S, Tiampo, K F, Samsonov, S V, Gonzalez, P J (2019) Modelling the elevation-dependent seasonal amplitude of tropospheric delays in GPS time-series using DInSAR and meteorological data. *Geophysical Journal International* 216 (1): 676-691; doi: 10.1093/gji/ggy443.
9. Ashena ZB, Ardestani VE, Camacho AG, Dehghani A, Fernández J (2018) Moho depth determination beneath Zagros Mountains from 3D inversion of gravity data. *Arabian Journal of Geoscience* 11(3): 52, https://doi.org/10.1007/s12517-018-3385-x.
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11. Béjar-Pizarro M, Notti D, Mateos RM, Ezquerro P, Centolanza G, Herrera G, Bru G, Sanabria M, Solari L, Duro J, Fernández J (2017) Mapping vulnerable urban areas affected by slow-moving landslides using InSAR. *Remote Sensing* 9: 876; doi: 10.3390/rs9090876.
12. Bevis M, Melini D, Spada G (2016) On computing the geoelastic response to a disk load. *Geophysical Journal International* 205: 1804–1812.
13. Bie L, Gonzalez PJ, Rietbrock A (2017) Slip distribution of the 2015 Lefkada earthquake and its implications for fault segmentation. *Geophysical Journal International* 210 (1): 420-427; doi: 10.1093/gji/ggx171.
14. Bie L, Hicks S, Garth T, Gonzalez PJ, Rietbrock A (2018) ‘Two go together’: Near-simultaneous moment release of two asperities during the 2016 Mw 6.6 Muji, China earthquake. *Earth and Planetary Science Letter*s 491: 34-42; doi: 10.1016/j.epsl.2018.03.033.
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