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

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 Rep.)
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 2015-2017 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 ongoing organization of the next Hotine-Marussi Symposium on Mathematical Geodesy which will be organized by ICCT in 2018, see below. The next meeting of the committee will be organized during the Joint Scientific Assembly of IAG and IASPEI, Kobe, Japan, in August 2017.

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 can be used by for fast and easy communication of ideas among the members of the Study Groups.

IX Hotine-Marussi Symposium

The highlight of the ICCT activities within the four-year period between IUGG General Assemblies is always the organization of the Hotine-Marussi Symposium on Mathematical Geodesy. Since the inception of ICCT, the already existing series of the Hotine-Marussi Symposia falls under the responsibility of ICCT. Earlier ICCT-organized symposia were the numbers VI (2006, Wuhan), VII (2009, Rome) and VIII (2013, Rome). The venue of the last two symposia was the Faculty of Engineering of the Sapienza University of Rome.

The next, IX, Hotine-Marussi symposium was supposed to be organized in 2017 following the traditional schedule of activities. However, based on the decision of the IAG Executive Committee, the next Hotine-Marussi symposium will be organized in early summer of 2018 in order to avoid the conflict with the IAG scientific meetings (next IAG scientific meeting will be organized this year in Kobe, Japan). The organization of the next Hotine-Marussi meeting is in preparation with two venue candidates (both in Italy) considered. Anticipated session topics will follow roughly the current study group structure of ICCT.

Further Meetings

The Hotine-Marussi Symposium is not the only scientific meeting with the visible presence of the ICCT. Session dedicated to recent general developments in geodetic theory were organized by ICCT-related personnel at the EGU General Assemblies 2016 and 2017 in Vienna. Other sessions on selected particular topics of theoretical geodesy related to joint study groups' activities were also organized at the EGU assemblies and at IAG's Commission 2 and Commission 4 meetings in Thessaloniki and Wroclaw, 2016. 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 midterm 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 level of detail and extent of the reports also vary and for the final report in 2019 more detailed instruction concerning the length, structure and level of detail will have to be explicitly specified. Some of the study groups also extended its memberships.

Most importantly, all chairmen but one delivered their report in time which confirms the main idea behind the current ICCT structure: involving young enthusiastic researchers as new study group chairmen who actively cooperate internationally at research topics which matter to current geodesy. Based on to-date activities of the groups, it is very likely they will stay operational until 2019 with the next Hotine-Marussi Symposium on Mathematical geodesy planned for 2018 highlighting the remaining two years of the period 2015-2019.

Only one study group did not submit its report; its continuation will be discussed at the ICCT and IAG EC meetings at the IAG/IASPEI Joint Scientific Meeting in Kobe, August 2017.

Joint Study Group 0.l0: High-rate GNSS

Chair: *Mattia Crespi (Italy)*

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 (China)*
- *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)*

Activities and publications during the period 2015-2017

Considering the Terms of Reference of JSG0.10, and specifically its objectives and program of activities, see http://icct.kma.zcu.cz/index.php/JSG0.10, the work outlined in the following report has been developed and is presently ongoing.

<u>Research</u>

1. Monitoring of ground shaking and displacement during earthquakes

- *GPS Seismology for moderate magnitude earthquake: analysis of the 31 October 2013 ML 6.4 Ruisui (Taiwan) earthquake*, see (Hung et al., 2017)
  The 31 October 2013 ML 6.4 Ruisui earthquake was well recorded by twelve 50-Hz, four 20-Hz and thirteen 1-Hz GPS receivers, and twenty-five strong motion stations located within the epicentral distance of about 90 km in eastern Taiwan. Kinematic positioning solutions estimated by four GNSS software (TRACK, RTKLIB, GIPSY and VADASE) were used to derive seismic waveforms and co-seismic displacements for this event; strong motion accelerometers were used to verify the capability of high rate GPS to detect body waves and surface waves, see Figure 1. Results showed that the coordinate repeatability of the GPS displacements time series are ~6 mm and ~20 mm standard deviation in the horizontal and vertical components respectively, after applying spatial filtering.

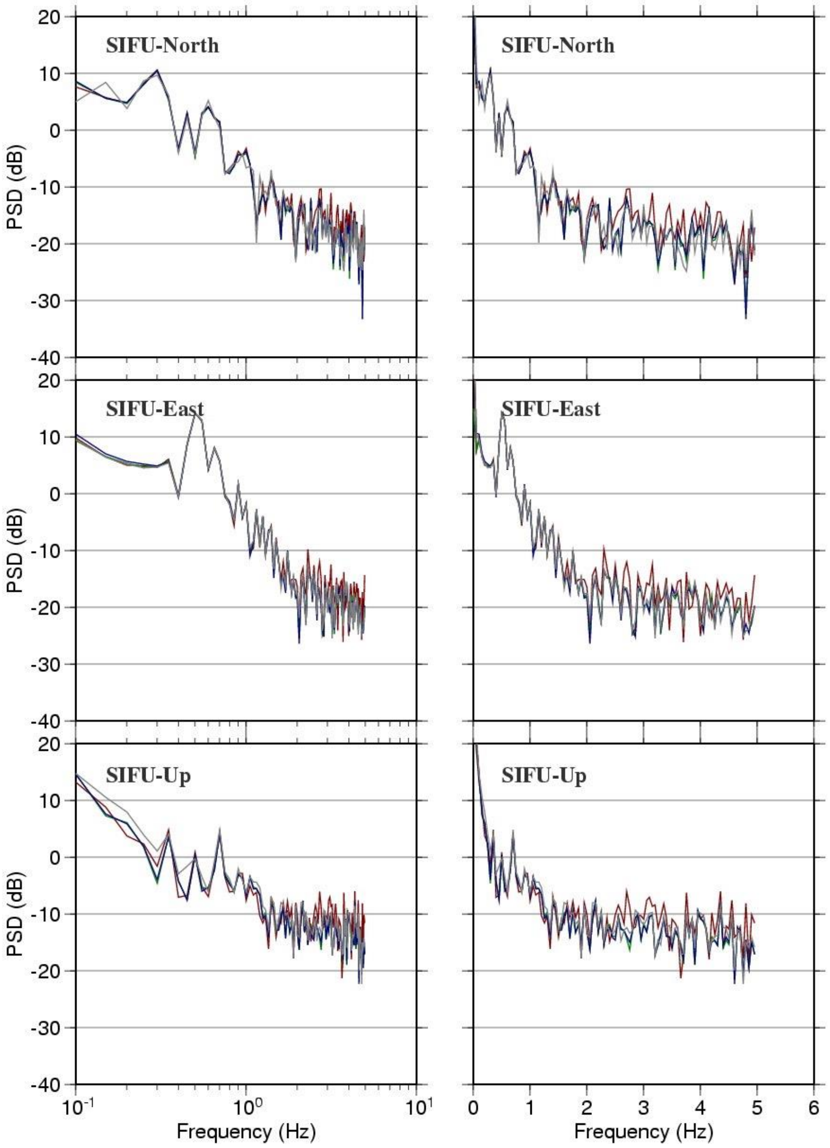

Figure 1: *Power spectral densities of the displacements time series at CGPS SIFU generated from the software TRACK (brown), GIPSY (green), RTKLIB in the PPP solution (blue) and VADASE (grey) in all three components*

- *Recent advances of the VADASE software to enhance reliability and accuracy of real-time displacement estimation*, see (Fratarcangeli et al., 2017)
  VADASE displacements might be impacted by two different effects: spurious spikes in velocities due to outliers (in this case, displacements, obtained through velocities integration, are severely corrupted), and trends in the displacements (mainly due to broadcast orbit and clock errors). Moreover, for applications to earthquakes (seismic inversion), it is quite useful to estimate in real-time the so-called coseismic displacement. These three issues (outliers in velocity, trends in displacements and real-time coseismic displacements) were addressed in recent advances of VADASE. Two strategies were introduced, respectively based on Leave-One-Out Cross Validation (VADASE–LOO) for a receiver autonomous outlier detection, and on a network augmentation strategy to filter common trend out (A–VADASE), see Figure 2. Moreover, a statistical test, based on the hypothesis of a constant mean level noise of the VADASE velocity estimates over few minutes, and a robust estimation procedure were introduced; they allow to estimate the overall coseismic displacement.

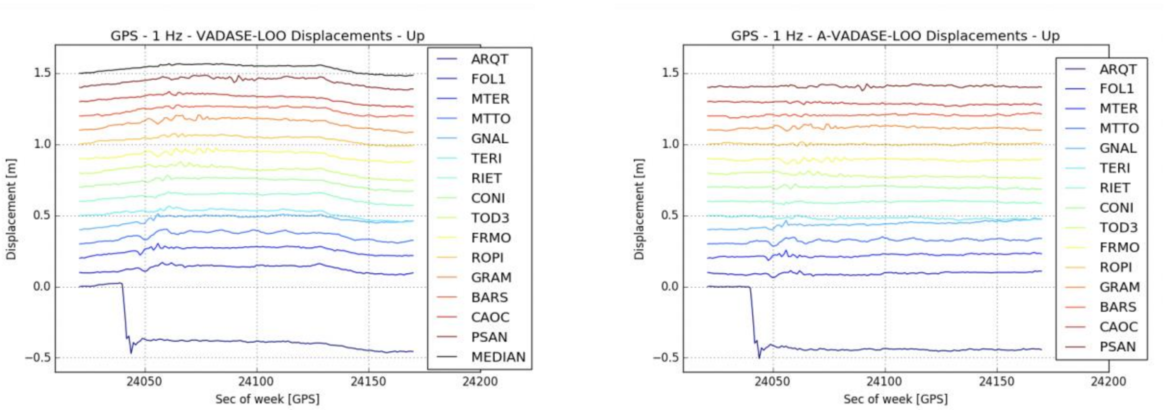

Figure 2: *Estimated displacements before (left) and after (right) trend removing by A–VADASE–LOO in the 150 s interval for the main shock of October 30, Mw 6.5 near Norcia (Perugia) earthquake, GPS time*

- *Error analysis of high-rate GNSS precise point positioning for seismic wave measurement*, see (Shu et al., 2017)
  A theoretical error analysis of PPP was carried out, together with the corresponding simulations within a short period of time, to fully understand the mechanism of mystified excellent performance of high-rate PPP within a short period of time. This analysis clearly indicated that the high-rate PPP errors consisted of two types: the residual systematic errors at the starting epoch, which affect high-rate PPP through the change of satellite geometry, and the time-varying systematic errors between the starting epoch and the current epoch. Also, real data experiments indicated that high-rate PPP can indeed achieve the millimetre level of precision in the horizontal components and the sub-centimetre level of precision in the vertical component to measure motion within a short period of time, see Figure 3. Moreover, the simulation results have clearly shown that the random noise of carrier phases and higher order ionospheric errors are two major factors to affect the precision within a short period of time. The experiments with real data have finally indicated that the precision of PPP solutions can degrade to the cm level in both the horizontal and vertical components, if the geometry of satellites is rather poor with a large DOP value.

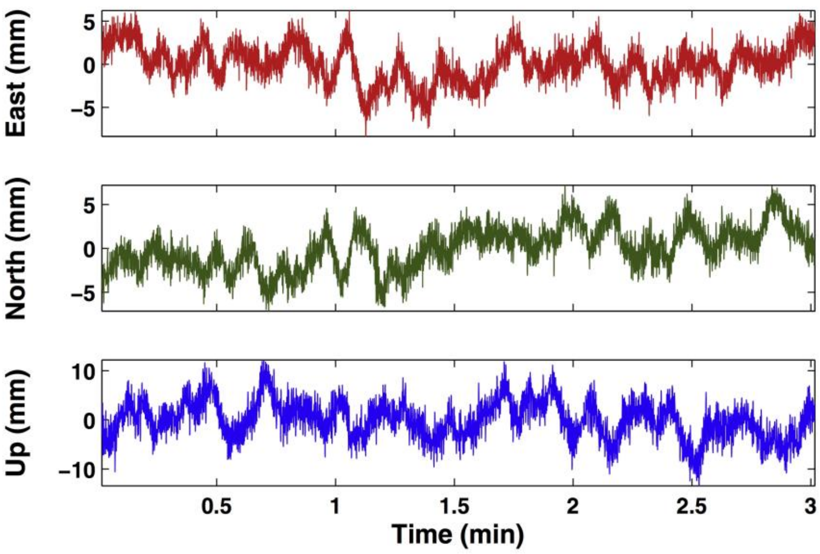

Figure 3: *PPP-derived displacements of waveform motion (mm)*

- *Integrated GPS/GLONASS for high-rate seismogeodesy*, see (Geng et al., 2017)
  The goal of this investigation is to check whether the positioning accuracy of high-rate GPS suffices in the identification of seismic signals, especially for relatively minor events. However, high-rate GPS is always obsessed by multipath effects. Although multipath effects can be partly mitigated through sidereal filtering, satellite orbits, atmosphere refractions, tides, etc. also contribute to the high-rate GPS noise. In addition, we have already been in a multi-GNSS environment where Russia's GLONASS has been in a full constellation since 2012 and the quality of its satellite orbit products by IGS has evolved into the quite similar level to the GPS counterpart. In this study, it was demonstrated that multi-GNSS will contribute significantly to reducing noise of high-rate displacements as compared to sidereal filtering, see Figure 4. The main conclusions are: 1) GPS sidereal filtering can potentially amplify errors on the lowest frequency band of a high-rate displacement time series; 2) integration with GLONASS reduces the noise of high-rate GPS by up to 40% over the entire frequency band of a displacement time series; and 3) high-rate multi-GNSS can be enhanced by sidereal filtering which is implemented to avoid complicating the noise spectrum.

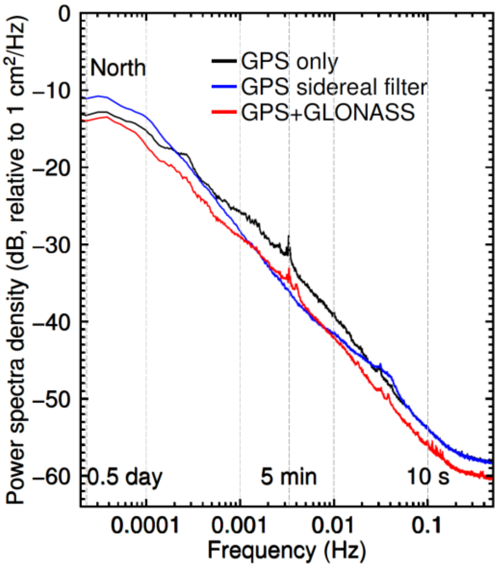

Figure 4: *Power spectral densities (PSD) of 1-Hz displacements in the north component derived from GPS-only, sidereally filtered GPS-only and integrated GPS/GLONASS solutions*

2. Tsunami early warning – Real-time detection of ionospheric perturbations

- *Real-time detection of Tsunami ionospheric disturbances with a stand-alone GNSS receiver: A preliminary feasibility demonstration*, see (Savastano et al., 2017)
  VARION (Variometric Approach for Real-Time Ionosphere Observation) is a novel algorithm able to estimate slant TEC (sTEC) variations in a real-time scenario. Using the VARION algorithm TEC variations at 56 GPS receivers in Hawaii as induced by the 2012 Haida Gwaii tsunami event were computed. TEC perturbations were observed with amplitudes of up to 0.25 TEC units and travelling ionospheric perturbations (TIDs), see Figure 5, moving away from the earthquake epicentre at an approximate speed of 316 m/s. A wavelet analysis to analyse localized variations of power in the TEC time series was performed and perturbation periods consistent with a tsunami typical deep ocean period were found. Finally, variations in TEC that

correlate in time and space with the tsunami waves were assessed, see Figure 6.

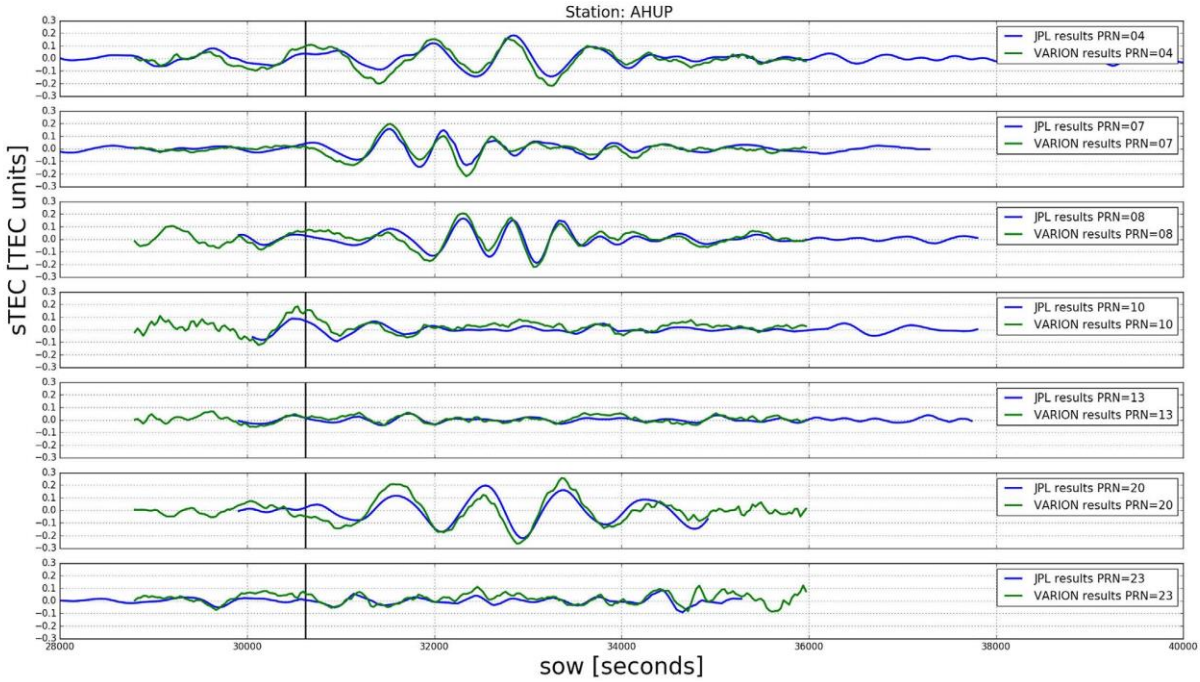

Figure 5. *Comparison between TEC time series obtained from the VARION and JPL techniques. TEC variations are computed for 7 satellites (PRNs 4, 7, 8, 10, 13, 20 and 23) in view from the AHUP station on the Hawaiian Islands. The black vertical line represents the time when the tsunami reached the Hawaiian Islands. TIDs were clearly detected, with good agreement between the two approaches.*

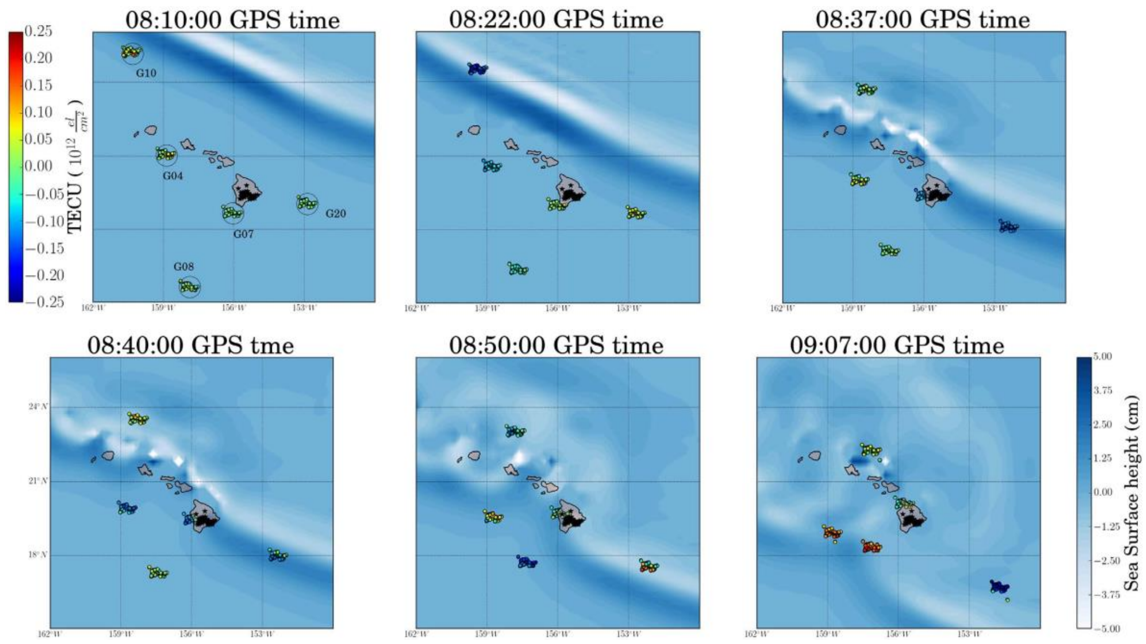

Figure 6. *Space-time sTEC variations at 6 epochs within the two hours interval (08:00 to 10:00 UT – 28 October 2012) at the SIPs for the 5 satellites showing TIDs, over-plotted the tsunami MOST model. TIDs are consistent in time and space with the tsunami waves.*

3. Real-time controlling landslides and the safety of structures

- *Exploiting performance of different low-cost sensors for small amplitude oscillatory motion monitoring: preliminary comparisons in view of possible integration*, see (Benedetti et al., 2016)

  The problem of low amplitude oscillatory motion detection through different low-cost sensors (LIS3LV02DQ MEMS accelerometer, Microsoft Kinect v2 range camera and uBlox 6 GPS receiver) was addressed. Several tests were performed using a one-direction vibrating table with different oscillation frequencies (in the range 1.5–3 Hz) and small challenging amplitudes (0.02 and 0.03 m). A Mikrotron EoSens high-resolution camera was used to give reference data. In the investigated time interval (in the order of tens of seconds) the results obtained indicate that displacements were detected with the resolution of fractions of millimetres with MEMS accelerometer and Kinect v2 and few millimetres with uBlox 6, see Table 1. MEMS accelerometer displays the lowest noise but a significant bias, whereas Kinect v2 and uBlox 6 appear more stable. The results suggest the possibility of sensor integration both for indoor (MEMS accelerometer + Kinect v2) and for outdoor (MEMS accelerometer + uBlox 6) applications and seem to be promising for structural monitoring applications.

		a [m/s^2]				v [m/s]				s [m]			
		RMSE	Mean	STD	R^2	RMSE	Mean	STD	R^2	RMSE	Mean	STD	R^2
f_1	MEMS	0.028	−0.002	0.028	0.99	0.004	0.000	0.004	0.99	0.0003	−0.0002	0.0002	0.99
	Kinect v2	0.415	−0.014	0.415	0.93	0.017	0.000	0.017	0.98	0.0009	−0.0005	0.0008	0.99
	uBlox	0.557	−0.003	0.557	0.85	0.029	0.000	0.029	0.95	0.0088	0.0000	0.0088	0.75
f_2	MEMS	0.037	−0.001	0.037	0.98	0.004	−0.001	0.004	0.99	0.0003	−0.0001	0.0003	0.98
	Kinect v2	0.651	−0.005	0.651	0.89	0.023	0.001	0.023	0.98	0.0010	0.0000	0.0010	0.99
f_3	MEMS	0.051	−0.005	0.051	0.98	0.004	−0.001	0.004	0.98	0.0003	−0.0001	0.0003	0.98
	Kinect v2	0.660	0.016	0.660	0.92	0.023	0.000	0.023	0.97	0.0009	0.0001	0.0009	0.99
f_4	MEMS	0.074	−0.007	0.074	0.93	0.012	0.011	0.007	0.93	0.0011	0.0010	0.0006	0.95
	Kinect v2	1.218	0.002	1.218	0.89	0.031	0.001	0.031	0.98	0.0009	0.0000	0.0009	0.99

Table 1: *Accuracy (RMSE), bias (mean) and noise (standard deviation) in test with 0.02 m amplitude*

4. Sensors integration

- *Comparison and integration of kinematic solutions from different sensors, in view of the realization of a unique device for high-rate observations embedding GNSS receiver and MEMS sensors*, see (Benedetti et al., 2016)

  The research was focused on the feasibility of merging the complementary benefits offered by MEMS accelerometers technology and GNSS, with an attention to low-cost sensors, in view of a low-cost integrated monitoring solution. The overall merging approach was set up at the level of the combination of kinematic results (velocities and displacements) coming from the two kinds of sensors, whose observations were separately processed, following to the so-called loose integration, which sounds much more simple and flexible thinking about the possibility of an easy change of the combined sensors, see Figures 7 and 8.

5. Providing detailed trajectories and kinematic parameters (not only position, but also velocity and acceleration) of high dynamic platforms

- *Accuracy assessment for kinematic estimation of position and velocity using pseudo-ranges and Doppler observables without ground truth applying a Monte Carlo-based numerical simulation*, see (Boffi and Wieser 2016)

  The ground truth is substituted by a reference trajectory (assumed to be the true one) and by a collection of assumptions about its geometry and its dynamics. A sensitivity analysis of the variable input parameter is performed, aiming to identify the influence of the uncertainties on the model output, see Figure 9.

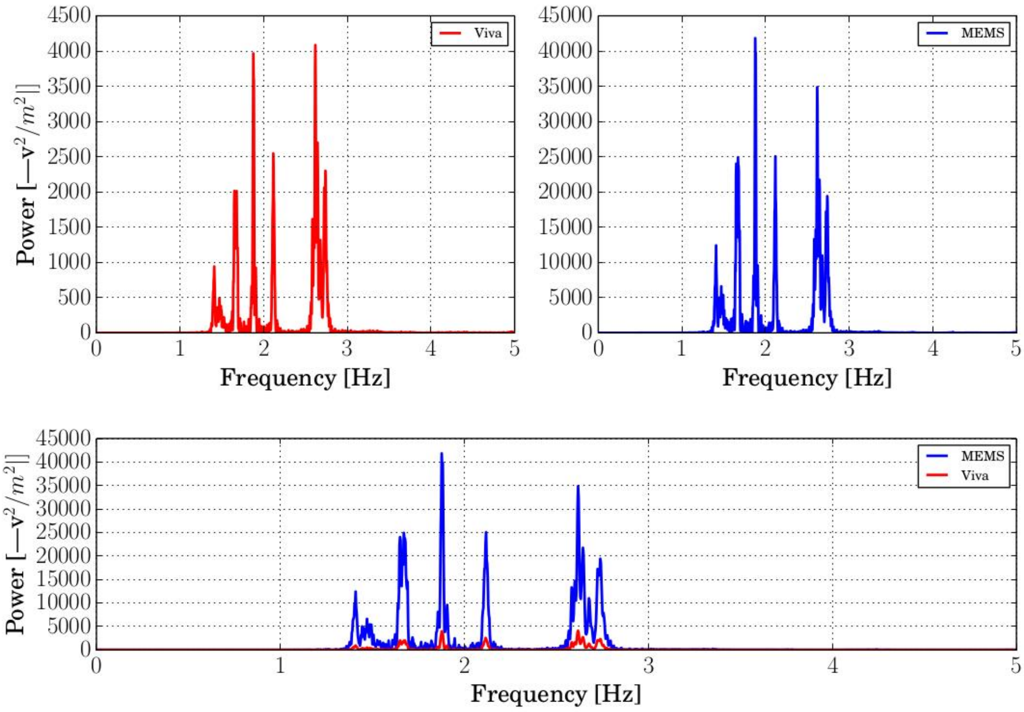

Figure 7: *GPS (10 Hz) and MEMS accelerometer (40 Hz) East velocity power spectra comparison*

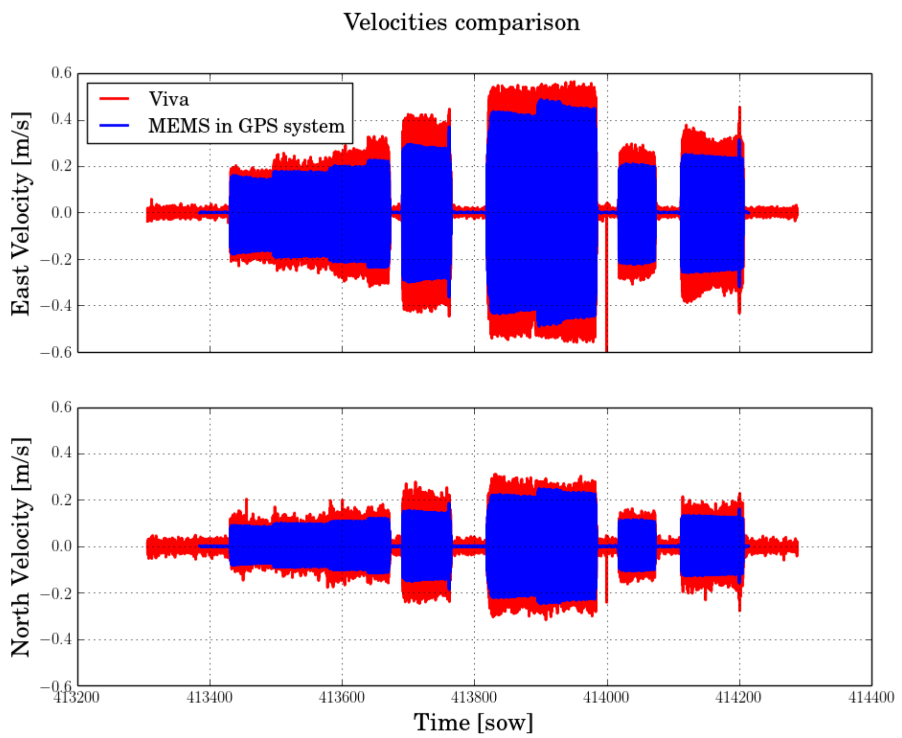

Figure 8: *GPS velocity solutions (10 Hz, computed with the VADASE software) in red compared with MEMS velocities (40 Hz, blue) transformed into the GPS reference system*

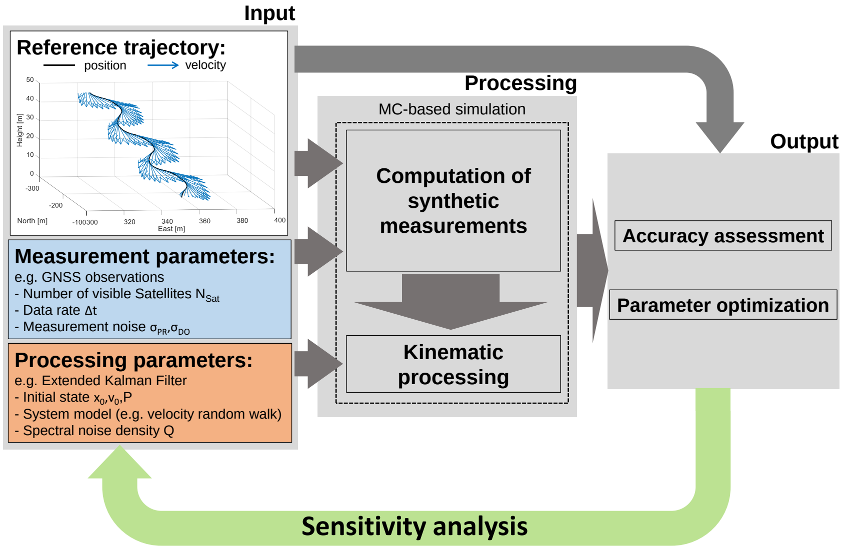

Figure 9: *Overview of the numerical simulation*

- *Investigation of a dynamics-based system noise adaption of an extended Kalman Filter for GNSS-only kinematic processing*, see (Branzanti et al., 2016)
  The MC-based approach is used to determine an optimum adaptive spectral noise density for each epoch, see Figure 10.

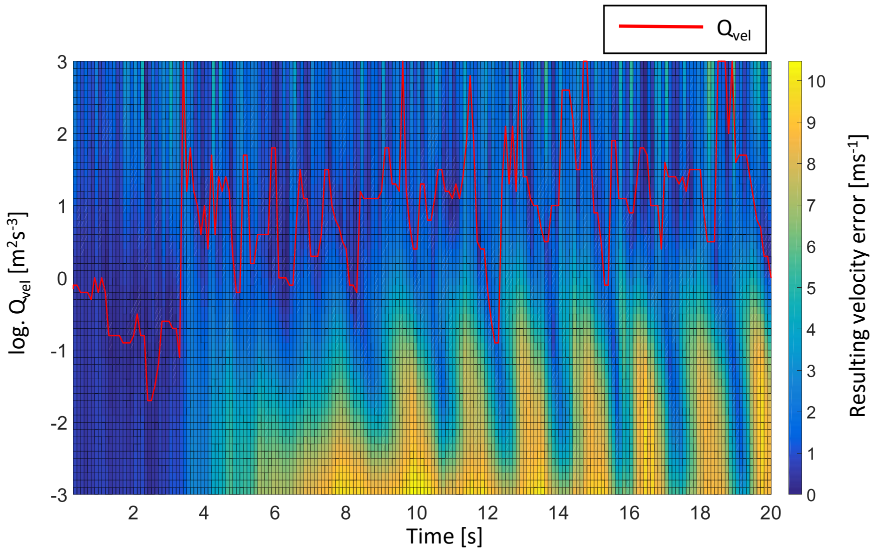

Figure 10: *Example of the identification of the optimal spectral noise density (Qvel) in a velocity random walk system model.*

- *Variometric approach for real-time GNSS navigation*, see (Branzanti et al., 2016)
  The Kinematic implementation of the Variometric Approach for Displacement Analysis Standalone Engine (Kin-VADASE) was investigated, giving a demonstration of its performances in the field of GNSS navigation. Kin-VADASE was applied to two test cases in order to estimate high rate (i.e., 10 Hz) kinematic parameters of moving vehicles. In this demonstration, data are collected and processed in the office, but the same results can be obtained in real-time through the implementation of Kin-VADASE in the firmware of a GNSS receiver. All the Kin-VADASE processing were

carried out using double- and single-frequency observations in order to investigate the potentialities of the software with geodetic class and low-cost single frequency receivers. Root Mean Square Errors in 3D with respect to differential positioning are at the level of 50 cm for dual frequency and better than 1 meter for single frequency data, see Figure 11.

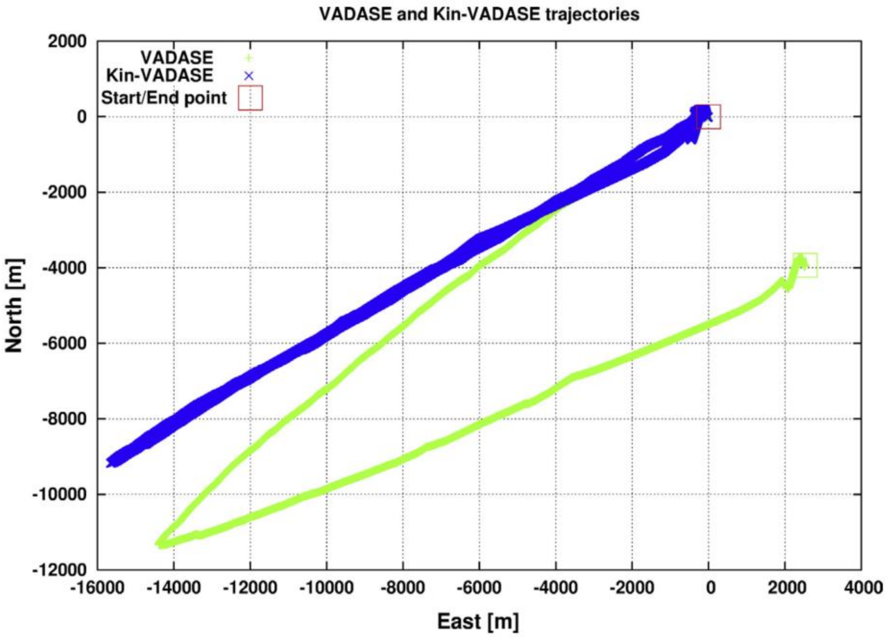

Figure 11: *Comparison between VADASE e KIN-VADASE*

6. Understanding geophysical/geodynamical processes mechanics
   - Investigations about the possibility to detect free oscillations (eigenmodes) of the Earth through a variometric approach (VADASE) were developed and are ongoing (Nico Sneeuw, Rudolf Widmer-Schnidrig, Giorgio Savastano, Mattia Crespi) – no publication at the moment.

7. High-speed terrestrial vehicles and athlete and sport vehicles monitoring
   - Application of GNSS for sport measurement for injury prevention and performance analysis, see (Boffi et al., 2016)
     The proposed approach aims to substitute a comparison with a reference measurement when the latter is unfeasible or impossible (e.g., over an extended capture volume and under high-dynamics).

<u>References</u>

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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 Xu (http://www.sciencedirect.com/science/journal/02731177/59/11)
This special issue is fully open access and aimed at the cutting edge accuracy potential of high-rate GNSS, its further possible improvement (by integration of multi-GNSS systems and/or with other sensors like Micro Electro-Mechanical System (MEMS) accelerometers), and applications. In details, the main covered topics are: 1) the analysis of the effect of a variety of error sources and high-rate products on high-rate precise point positioning, of the GNSS raw data quality and selection, and of the GNSS receiver tracking loop for high-rate GNSS applications; 2) the extension of the GNSS variometric approach for kinematic navigation applications, deformation and velocity measurement, aided with low-cost MEMS accelerometers; 3) the use of high-rate GNSS for the measurement of vibrations and accelerations of highly dynamical object motions and for structural health monitoring; and 4) the potential to establish a network real-time kinematic position and navigation system by using original GNSS observables.

Cooperation

The cooperation with the *GNSS Augmentation to the Tsunami Early Warning System Group* (GATEW), promoted and leaded by John LaBrecque within the GGOS Geohazards Monitoring Focus Area, was started.

Organization

1. Sessions at international congresses/symposia/workshops

   The *High-precision GNSS: methods, open problems and Geoscience applications* session at the European Geoscience Union 2017 General Assembly (April 2017) was organized. The organization of the *High-rate GNSS* session at the *IX Hotine-Marussi Symposium*, which will be held next year (June-July 2018) is ongoing.
2. Questionnaire

   It was launched a tentative questionnaire within the Members of the JSG for starting an inventory of methodologies, technologies and applications in high-rate GNSS (https://goo.gl/forms/eAKxgKuCpHYJFVJE3). On the basis of the collected answers and comments, the preparation of an updated version of the questionnaire to be spread within the GNSS Community is ongoing.

External impact of the research

1. 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)
2. 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)

Joint Study Group 0.11: Multiresolutional aspects of potential field theory

Chair: *Dimitrios Tsoulis (Greece)*

Members

- *Katrin Bentel (USA)*
- *Maria Grazia D'Urso (Italy)*
- *Christian Gerlach (Germany)*
- *Wolfgang Keller (Germany)*
- *Christopher Kotsakis (Greece)*
- *Michael Kuhn (Australia)*
- *Volker Michel (Germany)*
- *Pavel Novák (Czech Republic)*
- *Konstantinos Patlakis (Greece)*
- *Clément Roussel (France)*
- *Michael Sideris (Canada)*
- *Jérôme Verdun (France)*

Corresponding members

- *Christopher Jekeli (USA)*
- *Frederik Simons (USA)*
- *Nico Sneeuw (Germany)*

Activities and publications during the period 2015-2017

The Study group had its first meeting at the 1st Joint Commission 2 & IGFS Symposium, 19-23 September 2016 in Thessaloniki. There, it verified its main objective, which is the mathematical description and numerical computation of the gravity signal of finite distributions. Specific areas of work have been identified, including the comparison and assessment between different analytical, numerical and hybrid solutions, applications over finite regions in the frame of classical terrain correction computations, band limited validation against available Earth gravity models, bibliographical survey and identification of multiresolutional techniques for expressing the gravity field signal of given distributions. Session G1.3 *Analytical, numerical and multiresolutional techniques for forward modelling of gravitational fields of mass distributions* has been organized at the EGU General Assembly 2017, 23–28 April 2017, in Vienna, which was convened by four members of the Study Group.

The Study Group is affiliated with IAG Commissions 2 (Gravity Field) and 3 (Earth Rotation and Geodynamics) and GGOS. Its webpage is http://icct.kma.zcu.cz/index.php/JSG0.11.

References

Amna I, Michel V (2017) Pseudodifferential operators, cubature and equidistribution on the 3D-ball – an approach based on orthonormal basis systems. *Numerical Functional Analysis and Optimization*, in press.

D'Urso MG (2015) The gravity anomaly of a 2d polygonal body having density contrast given by polynomial functions. *Surveys in Geophysics* 36: 391–425

D'Urso MG, Trotta S (2017) Gravity anomaly of polyhedral bodies having a polynomial density contrast. *Surveys in Geophysics*, DOI 10.1007/s10712-017-9411-9

Gutting M, Kretz B, Michel V, Telschow R (2017) Study on parameter choice methods for the RFMP with respect to downward continuation. *Mathematics of Computation and Data Science*, in press.

Hirt C, Reußner E, Rexer M, Kuhn M (2016) Topographic gravity modelling for global Bouguer maps to degree 2160: Validation of spectral and spatial domain forward modelling techniques at the 10 mGal level. *Journal of Geophysical Research* 121(9): 6846–6862

Kuhn M, Hirt C (2016) Topographic gravitational potential and second-order derivatives: an examination of approximation errors caused by rock-equivalent topography (RET). *Journal of Geodesy* 90(9): 883-902

Plattner A, Simons FJ (2017) Internal and external potential-field estimation from regional vector data at varying satellite altitude. *Geophysical Journal International*, in press.

Root BC, Novák P, Dirkx D, Kaban M, van der Wal W, Vermeersen LLA (2016) On a spectral method for forward gravity field modelling. *Journal of Geodynamics* 97: 22-30

Roussel C, Verdun J, Cali J, Masson F (2015) Complete gravity field of an ellipsoidal prism in spherical coordinates by Gauss-Legendre quadrature. *Geophysical Journal International* 203(3): 2220-2236

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

Tsoulis D, Patlakis K (2017) Investigating the effect of different terrain modelling techniques on the computation of local gravity anomalies, EGU General Assembly 2017, Session G1.3, *Analytical, numerical and multiresolutional techniques for forward modelling of gravitational fields of mass distributions*, 23–28 April 2017, Vienna.

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

Chair: *Róbert Čunderlík (Slovak Republic)*
Vice Chair: *Karol Mikula (Slovak Republic)*

Members

- *Jan Martin Brockmann (Germany)*
- *Walyeldeen Godah (Poland)*
- *Petr Holota (Czech Republic)*
- *Michal Kollár (Slovak Republic)*
- *Marek Macák (Slovak Republic)*
- *Karol Mikula (Slovak Republic)*
- *Zuzana Minarechová (Slovak Republic)*
- *Otakar Nesvadba (Czech Republic)*
- *Wolf-Dieter Schuh (Germany)*

Activities and publications during the period 2015-2017

Activities of JSG-0.12 during the period 2015−2017 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) discretization methods like the boundary element method (BEM), finite element method (FEM) and finite volume method (FVM), (ii) meshless methods like the method of fundamental solution (MFS) and singular boundary method (SBM), and 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. 2016b, Holota 2016, Holota and Nesvadba 2017a,b, Macák et al. 2016 and Medľa et al. 2017,
- to process the GOCE satellite measurements, see Čunderlík 2016a,
- to develop nonlinear diffusion filtering of various geodetic data, see, e.g., Kollár et al. 2016a, and Čunderlík et al. 2016a.

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 Message Passing Interface (MPI).

In the following main activities investigated during the period 2015−2017 are briefly described:

In case of FVM, 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 have 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 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., 2017).

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 efficiently be compressed through an approach very similar to the column-pivoted LU decomposition. The first experiments (Čunderlík and Vipiana 2017) 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 considerably a level of the discretization 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 that now depends on a combination of the edge detector and mean curvature of the filtered function. A semi-implicit numerical scheme has been derived for this approach (Kollár et al., 2016a), 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., 2016a). The similar semi-implicit numerical scheme has been also derived for data given on 2D rectangular grids (Kollár et al., 2017).

The achieved results 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 Vienna (April 2016, and April 2017) within the session "Recent Developments in Geodetic Theory" or during the 1st Joint Commission 2 and IGFS Meeting – International Symposium on Gravity, Geoid and Height Systems 2016 (GGHS-2016) in Thessaloniki (September 2016).

References

Čunderlík R (2016a) 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

Čunderlík R, Kollár M, Mikula K (2016a) Filters for geodesy data based on linear and nonlinear diffusion. GEM - *International Journal on Geomathematics* 7(2): 239-274

Holota P (2016) Domain transformation and the iteration solution of the linear gravimetric boundary value problem. *IAG Symposia Series,* DOI 10.1007/1345_2016_236 (in press).

Kollár M, Čunderlík R, Mikula K (2016a) 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

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

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

Medľa M, Mikula K, Čunderlík R, Macák M (2016) Numerical solution to the oblique derivative boundary value problem on non-uniform grids above the earth topography. *Journal of Geodesy* (accepted in June 2017).

Nesvadba O, Holota P (2016) An ellipsoidal analogue to Hotine's kernel: accuracy and applicability. *IAG Symposia Series* 144: 93-100

Nesvadba O, Holota P (2016) An OpenCL implementation of ellipsoidal harmonics. *IAG Symposia Series* 142: 195-203

Roese-Koerner L, Schuh W-D (2016) Effects of different objective functions in inequality constrained and rank-deficient least-squares problems. *IAG Symposia Series* 142: 325-331

<u>Selected oral and poster presentations</u>

EGU-2017 (Wien, April 2017)

Čunderlík R, Vipiana F (2017) Hierarchical matrices implemented into the boundary integral approaches for gravity field modelling. EGU2017-7294

Holota P, Nesvadba O (2017a) 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. EGU2017-15962

Holota P, Nesvadba O (2017b) Laplacian versus topography in the solution of the linear gravimetric boundary value problem by means of successive approximations. EGU2017-19061

Kollár M, Čunderlík R, Mikula K (2017) Nonlinear diffusion filtering methods locally adapted to data features. EGU2017-7340

Macák M (2017) Domain decomposition methods in FVM approach to gravity field modelling. EGU2017-7232

GGHS-2016 (Thessaloniki, September 2016)

Brockmann JM, Schuh W-D (2016) Stochastic modelling of altimetric sea surface height measurements – refined AR models from iterative residual analysis. http://gghs2016.com/presentation-info/?presentation=747

Čunderlík R (2016b) Numerical solution of the oblique derivative BVP on the Earth's surface topography using BEM. http://gghs2016.com/presentation-info/?presentation=717

Čunderlík R (2016c) Off-sets between tide gauges estimated from the filtered GOCE-based satellite-only MDT. http://gghs2016.com/presentation-info/?presentation=740

Čunderlík R, Macák M, Minarechová Z, Mikula K (2016b) High-resolution modelling of the altimetry-derived gravity data using FVM.
http://gghs2016.com/presentation-info/?presentation=695

Holota P, Nesvadba O (2016a) Modification of ellipsoidal coordinates and successive approximations in the solution of the linear gravimetric boundary value problem. http://gghs2016.com/presentation-info/?presentation=957

EGU-2016 (Wien, April 2016)

Čunderlík R, Špir R, Mikula K (2016c) Numerical solution of the exterior oblique derivative BVP using the direct BEM formulation. EGU2016-5735

Holota P, Nesvadba O (2016b) 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. EGU2016-5735

Kollár M, Mikula K, Čunderlík R (2016b) Non-linear diffusion filtering influenced by mean curvature. EGU2016-5837

Macák M, Mikula K (2016) Optimization of solving the boundary-value problems related to physical geodesy. EGU2016-6027

Medľa M, Mikula K, Macák M (2016) Finite volume method for geodetic boundary value problem. EGU2016-5789

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

Chair: *Michal Šprlák (Australia)*

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)*

Activities and publications during the period 2015-2017

As the objectives of JSG0.13 are primarily of the theoretical nature, its members have focused on mutual cooperation and publishing their findings in the international journals on geodesy and geophysics, including the high-ranked journals, such as Journal of Geodesy, Geophysical Journal International, Remote Sensing, Surveys in Geophysics, and Earth-Science Reviews. This effort has resulted in more than 30 peer-reviewed articles suggesting an active and actual field of research.

The list of selected peer-reviewed publications is provided below. The scientific articles have attempted to address all objectives of JSG0.13. The works by P. Novák, M. Pitoňák, and M. Šprlák have mainly been focused on theoretical and numerical aspects of the spherical integral transforms. I. Foroughi has considered the same geometrical approximation of the Earth, while exploiting the apparatus of the radial basis functions. On the other hand, the studies by P. Holota and O. Nesvadba have been devoted to the systematic solution of boundary value problems for the ellipsoidal (spheroidal) geometry. The scientific contributions by M. Eshagh and R. Tenzer have even reached beyond the specified objectives of JSG0.13 as the theoretical apparatus of integral transforms/equations may be exploited for numerous applications in geophysics.

One of JSG0.13 activities has been aimed to provide a bibliographic list of existing publications that cover the scopes of the study group. Four members of JSG0.13 published a review article that summarizes spherical integral transforms between various quantities of the gravitational field up to the components of the third-order gravitational tensor, see (Novák et al. 2017). The article includes an extensive list of publications devoted to the spherical integral transforms and may be of interest for scientists from many disciplines, e.g., geosciences, mathematics, and physics. It also represents a significant advancement towards the proposal of suitable generalized notation for a variety of classical and new integral equations in geodesy for the spherical approximation.

Members of JSG0.13 have actively presented their scientific achievements 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 the sessions on gravity field modelling, satellite missions, vertical reference systems, boundary value problems, or theoretical advances in geodesy. The list of selected oral and poster presentations is provided below.

Except for the scientific activities, members of JSG0.13 have also been responsible for organizing international conferences. Namely, P. Holota and O. Nesvadba organized the session G1.1 called "Recent Developments in Geodetic Theory", which is regularly held at EGU General Assembly, and is closely related to the objectives of the study group.

References

Eshagh M (2015) On the relation between Moho and sub-crustal stress induced by mantle convection. *Journal of Geophysics and Engineering* 12: 1-11.

Eshagh M (2016) A theoretical discussion on Vening Meinesz-Moritz inverse problem of isostasy. *Geophysical Journal International* 207: 1420-1431.

Eshagh M (2016) Integral approaches to determine sub-crustal stress from terrestrial gravimetric data. *Pure and Applied Geophysics* 173: 805-825.

Eshagh M (2016) On Vening-Meinesz-Moritz and flexural theories of isostasy and their comparison over Tibet Plateau. *Journal of Geodetic Science* 6: 139-151.

Eshagh M (2017) Local recovery of lithospheric stress tensor from GOCE gravitational tensor. *Geophysical Journal International* 209: 317-333.

Eshagh M, Ebadi S, Tenzer R (2017) Isostatic GOCE Moho model for Iran. *Journal of Asian Earth Sciences* 138: 12-24

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

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

Eshagh M, Hussain M, Tenzer R, Romeshkani M (2016) Moho density contrast in central Eurasia from GOCE gravity gradients. *Remote Sensing* 8: 1-18

Eshagh M, Hussain M, Tiampo KF (2016) Towards sub-lithospheric stress determination from seismic Moho, topographic heights and GOCE data. *Journal of Asian Earth Sciences* 169: 1-12

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

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

Eshagh M, Tenzer R (2015) Sub-crustal stress determined using gravity and crust structure models. *Computational Geoscience* 19: 115-125

Foroughi I, Afrasteh Y, Ramouz S, Safari A (2017) Local evaluation of Earth Gravitational Models, case study: Iran. *Geodesy and Cartography* 43: 1-13

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

Holota P (2015) Domain transformation and the iteration solution of the linear gravimetric boundary value problem. In: 26th IUGG General Assembly, Prague, Czech Republic, June 22 - July 2, 2015, *IAG Symposia Series*, Springer. DOI 10.1007/1345_2016_236, pp. 1-6, ISSN 0939-9585.

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).

Nesvadba O, Holota P (2016) An ellipsoidal analogue to Hotine's kernel: accuracy and applicability. In: Jin S, Barzaghi R (Eds.) Third International Gravity Field Service (IGFS) General Assembly (IGFS2014), Proceedings of the Symposium in Shanghai, 30 June - 6 July, 2014, *IAG Symposia* Series 144: 93-100, doi: 10.1007/1345_2015_133, ISSN 0939-9585.

Nesvadba O, Holota P (2016) An open CL implementation of ellipsoidal harmonics. In: Sneeuw N, Novák P, Crespi M, Sansò F (Eds.): VIII Hotine-Marussi Symposium on Mathematical Geodesy. Proceedings of the Symposium in Rome, 17-21 June, 2013. IAG Symposia Series 142: 195-203, doi: 10.1007/1345_2015_59, ISBN 978-3-319-24548-5, ISSN 0939-9585.

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

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(1): 89-98

Pitoňák M, Šprlák M, Novák P, Tenzer R (2017) Regional gravity field modelling from GOCE observables. *Advances in Space Research* 59(1): 114-127

Pitoňák M, Šprlák M, Tenzer R (2017) Possibilities of inversion of satellite third-order gravitational tensor onto gravity anomalies: a case study for central Europe. *Geophysical Journal International* 209(2): 799-812

Romeshkani M, Eshagh M (2015) Deterministically-modified integral estimators of tensor of gravitation. *Boletim de Ciências Geodésicas* 21: 189-212

Shahbazi A, Safari A, Foroughi I, Tenzer R (2016) A numerically efficient technique of regional gravity field modelling using radial basis functions. *Comptes Rendus Geoscience* 348: 99-105

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

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.

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

Šprlák M, Novák P (2016) Spherical gravitational curvature boundary-value problem. *Journal of Geodesy* 90: 727-739

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

Šprlák M, Novák P, Pitoňák M (2016). Spherical harmonic analysis of gravitational curvatures and implications for future satellite mission. *Surveys in Geophysics* 37(3): 681-700

Tenzer R, Eshagh M (2015) Subduction generated sub-crustal stress in Taiwan. *Terrestrial, Atmospheric and Oceanic Sciences* 26: 261-268

Tenzer R, Eshagh M, Jin S (2015) Martian sub-crustal stress from gravity and topographic models. *Earth and Planetary Science Letters* 425: 84-92

Tenzer R, Eshagh M, Shen W (2017) The subcrustal stress estimation in central Eurasia from gravity, terrain and crustal structure models. *Geoscience Journal* 21: 47-54

Tenzer R, Foroughi I, Pitoňák M, Šprlák M (2017) Effect of the Earth's Inner Structure on the Gravity in Definitions of Height Systems. *Geophysical Journal International* 209: 297-316

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.

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, 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) 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.

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, 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, 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, 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, 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, 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, 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.

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, Novák P (2016) Spherical gravitational curvature boundary-value problem. Gravity, Geoid and Height Systems 2016, Thessaloniki, Greece, September 2016.

Šprlák M, Novák P, Pitoňák M, Hamáčková E (2015) Solution of the boundary value problems with boundary conditions in the form of gravitational curvatures. AGU Fall Meeting, San Francisco, December 2015.

Šprlák M, Novák P, Pitoňák M, Hamáčková E (2015) Spherical harmonic analysis of third-order gravitational tensor components and its implications for future gravity-dedicated satellite mission designs. 26th IUGG General Assembly, Prague, June-July 2015.

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

Chair: *Krzysztof Sośnica (Poland)*

Members

- *Toshimichi Otsubo (Japan)*
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- *Mathis Bloßfeld (Germany)*
- *Andrea Grahsl (Switzerland)*
- *Grzegorz Bury (Poland)*
- *Radosław Zajdel (Poland)*
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- *Agnieszka Wnęk (Poland)*
- *Sara Bruni (Italy)*
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Activities and publications during the period 2015-2017

The activities of JSG0.21 were concentrated around the identification of systematic effects between different techniques of satellite and space geodesy. A proper identification and handling of systematics should in result improve the consistency between different observational techniques, and should help us to mitigate artefacts in the geodetic time series. Therefore, different observational techniques of space geodesy, which are capable of deriving the same parameters, are cross-validated and combined. Geodetic parameters that can be determined employing different techniques of space geodesy are thus the fundamental subject of interest in JSG0.21.

The activities of JSG0.21 in the period 2015-2017 included in particular:

1. development of an online service with the validation results of multi-GNSS orbits using Satellite Laser Ranging (SLR) data and for the identification of systematic biases at SLR stations and the assessment of the multi-GNSS orbit quality,
2. comparison and combination of low-degree Earth's gravity field coefficients (including geocenter motion) derived from SLR, GRACE and GNSS data,
3. comparison and assimilation of the tropospheric delays based on SLR, GNSS, radiosonde, and numerical weather models.

<u>Online service for validation of multi-GNSS orbits using SLR</u>

In the recent years the geodetic community could observe an advent of new GNSS systems. GLONASS reached its full operational capability in 2010. The constellation of Galileo satellites reached the number of 18 spacecraft in 2017, including two satellites in high eccentric orbits. BeiDou reached its full operational capability above Eastern Asia and is being now extended towards the global coverage. QZSS consists now of one QZS-1 satellite. More satellites and more systems impose not only opportunities for space geodesy, but also introduce considerable challenges for a proper combination of different systems.

All 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 devoted to tracking new Galileo spacecraft, as well as tracking of the whole GNSS constellation. Such an initiative introduces a challenge for SLR stations, as the number of GNSS targets for tracking exceeds now 70 satellites, which is by far more than, e.g., 10 or 20 years ago. 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, geocentre motion, etc. Fusion of GNSS and SLR observations requires a profound investigation of biases and systematic effects affecting both techniques. Neglecting systematic effects may lead to a degradation of solutions and the absorption of various systematic effects by global geodetic parameters (Sośnica et al., 2015, 2017).

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, http://multi-slrgnss.rhcloud.com/slr/). The service has been developed in the framework of the JSG0.21 activities.

Orbit determination of new GNSS spacecraft is very challenging due to different construction of satellites (size and shape of satellite body, various absorption and reflection characteristics of satellite surfaces, different sizes of solar panels), different characteristics of the orbits (MEO, GEO, inclined, circular, eccentric, etc.), different revolution periods of satellites, different numbers of orbital planes, different power of transmitting antennas, and different nominal steering of spacecraft: yaw-steering, dynamic yaw-steering, and the normal altitude. All of those issues may generate systematic errors in estimated orbits when such effects are not properly taken into account. Today, the multi-GNSS orbits are generated by various MGEX Analysis Centers on the basis of microwave GNSS observations. SLR serves as an independent technique for the validation of orbit quality for new GNSS, as an indicator of orbit errors explicitly included in satellite orbits. Figure 12 shows an example of the distribution of SLR-GNSS residuals for GLONASS and Galileo tracked by Yarragadee (left); and Galileo and BeiDou tracked by Shanghai (right). The mean residuals to GLONASS are shifted toward negative values with a mean offset of -11 mm for Yarragadee. This shift is mostly caused by the satellite signature effect and is related to multi-photo detectors used at SLR sites (Sośnica et al., 2016). The mean SLR residuals for Galileo are shifted towards negative values due to missing modelling of antenna thrust and albedo for new spacecraft. Similar effect is visible for the both, Yarragadee and Shanghai stations.

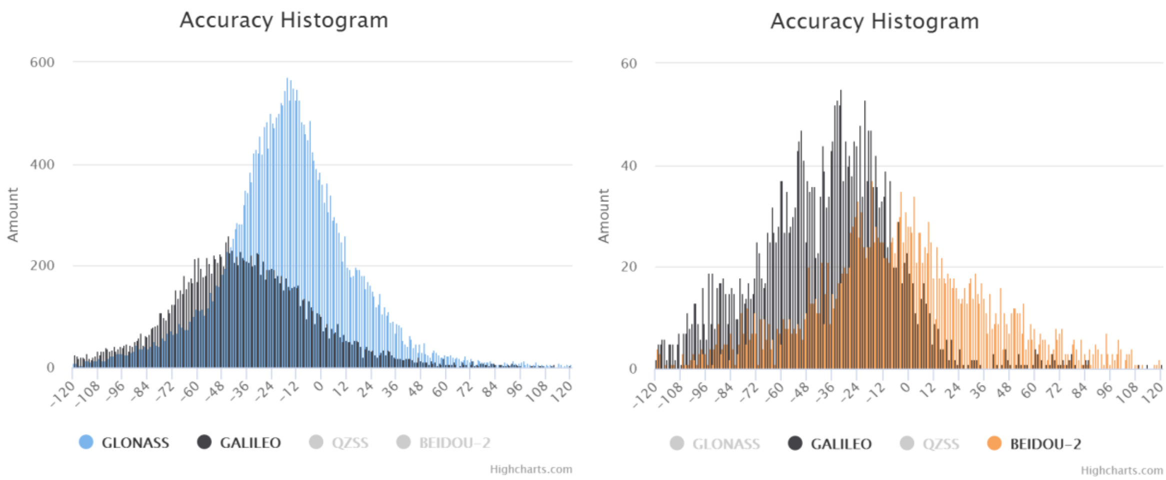

Figure 12. *Distribution of the SLR residuals in mm with respect to CODE microwave GLONASS, Galileo and Beidou orbits for Yarragadee (left) and Shanghai (right). Plots were generated using the on-line GOVUS service (http://multi-slrgnss.rhcloud.com/).*

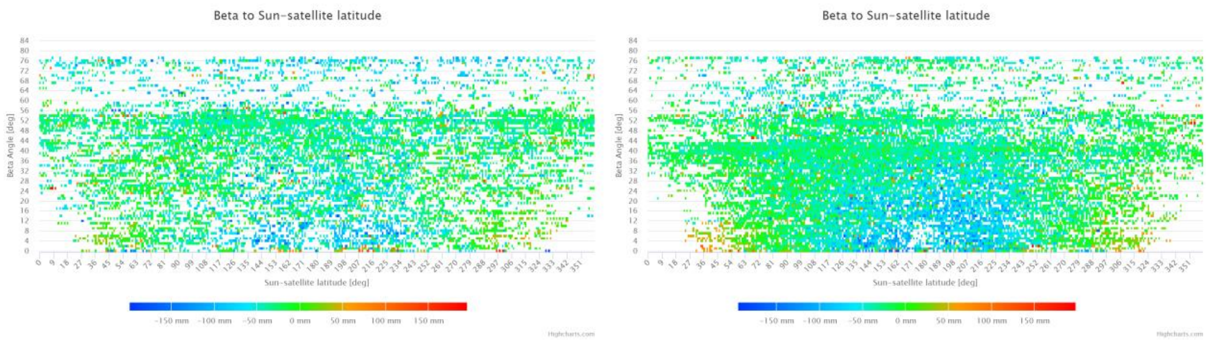

Figure 13. *SLR residuals as a function of the Sun elevation angle above the orbital plane (Beta) and the satellite argument of latitude with respect to the latitude of the Sun for Galileo IOV satellites (left) and Galileo (FOC) for the period 2016.0-2017.4. Plots were generated using the on-line GOVUS service (http://multi-slrgnss.rhcloud.com/).*

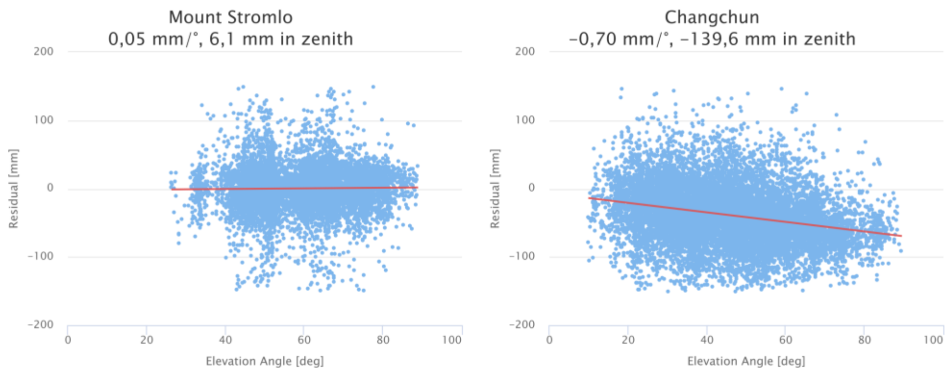

Figure 14. *Dependency between SLR residuals and the elevation angle of satellite over horizon for a station without systematic effects (Mount Stromlo, left) and a station with a clear systematic pattern (Changchun, right). Plots were generated using the on-line GOVUS service (http://multi-slrgnss.rhcloud.com/).*

SLR residuals can also be used for validation of the solar radiation pressure models, especially for the newly launched spacecraft. Figure 13 shows a comparison between SLR residuals for Galileo IOV (left) and Galileo FOC (right) when using the new Empirical CODE Orbit Model (ECOM2, Arnold et al., 2015; Prange et al., 2017). Figure 13 suggests that despite using ECOM2, many systematic effects still exist, which is visible for FOC satellites and low *Beta* angles.

The GOVUS service can be used not only for the assessment of the quality of multi-GNSS orbits, but also may serve as an indicator for various systematic errors affecting the SLR stations and limiting the consistency between SLR and GNSS techniques. Figure 14 shows a dependency between SLR residuals and the satellite elevation angle as seen from the SLR station for Mount Stromlo (left) and Changchun (right). In case of Changchun, a clear systematic effect is obtained which is a conjunction of the satellite signature effect and a bias at the station.

Combination of low-degree Earth's gravity field coefficients

The second main activity of JSG0.21 is related to cross-validation and combination of low-degree Earth's gravity field coefficients derived from GRACE and SLR data (Bloßfeld et al., 2017). In the framework of the EGSIEM project (European Gravity Service for Improved Emergency Management founded by the European Union's Horizon 2020 research and innovation programme, Jäggi et al., 2015) several European institutions combine their monthly gravity field models based on GRACE data. University of Bern, which is a leader in EGSIEM, proposed a similar solution for SLR gravity field models under the umbrella of EGSIEM. Five members of the JSG0.21 group are involved in generating SINEX files with normal equation systems containing the low-degree gravity field coefficients based on SLR data only. This activity was initiated in January 2017 in Bern starting with the adoption of common processing standards for all groups (Bloßfeld et al., 2017). The combined SLR solutions will help to minimize various systematic errors included in specific single solutions. The resulting SLR combined monthly gravity field models will be compared and combined with GRACE, which will help to further investigate observation-specific errors included in each of the observation techniques.

Degree-1 gravity field coefficients, corresponding to the geocenter motion, derived from GNSS, SLR and high-degree GRACE-based data were also compared using wavelet-based semblance filtering (Kosek, 2014; Wnęk et al., 2016). Such a solution allows identifying and extracting a common geophysical signal from the time series of geocenter coordinates based on different observation principles. Wavelet semblance enables also extracting technique-specific artefacts, such as draconitic years, from the geocentre series.

Comparison and assimilation of the tropospheric delays

The third area of activities within JSG0.21 was related to comparison and assimilation of the tropospheric delays based on SLR, GNSS, radiosonde, and numerical weather models. Figure 15 shows that the total refractivity of the troposphere is much better reconstructed when using a combination of GNSS and numerical weather model prediction (WRF) data employing the least squares collocation method (left) as compared to the solution based on GNSS-only (right). As a result, the combined GNSS-WRF model provides much more reliable information on the water vapour content than GNSS-only or WRF-only data (Wilgan et al., 2017a, 2017b).

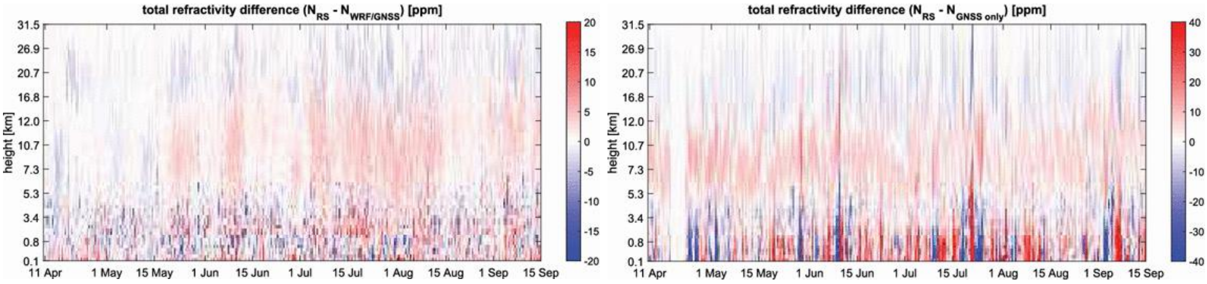

Figure 15. *Differences of the total refractivity derived from radiosondes (RS), numerical Weather Research and Forecasting (WRF) model combined with GNSS-derived parameters using the collocation method (left) and differences between total refractivity from RS and GNSS-only (right) in 2014, after Wilgan et al., (2017a).*

Improving the troposphere delay modelling is important not only for the recovery of the tropospheric state, but also for the improvement of GNSS positioning, using, e.g., Precise Point Positioning technique, and for SLR solutions. In the SLR solutions, the horizontal gradients of the troposphere delay are currently neglected both in the SLR operational products and in the reprocessed products which are used for the definition of the International Terrestrial Reference Frame. As a result, the horizontal components of SLR solutions are typically affected by systematic errors associated with the mismodeling of horizontal gradients of the troposphere delay, whereas in the other techniques, such as GNSS and VLBI, gradients are considered. However, most of the SLR stations are co-located with GNSS receivers; thus, it is possible to compare the SLR-derived and GNSS-derived gradients (see Fig. 16), even when the number of SLR is typically too small to derive gradients of a reliable quality. Using the numerical weather models as a source data for the SLR horizontal gradients may improve the quality and stability of SLR solutions (Drożdżewski and Sośnica, 2017).

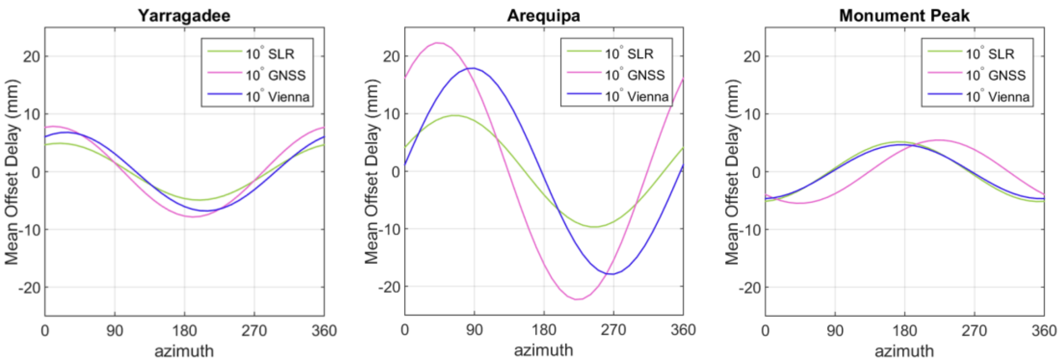

Figure 16. *Horizontal gradients of the troposphere delay derived from SLR, GNSS and numerical weather models (Vienna, Boehm et al., 2009) mapped onto the elevation angle of 10 arc-deg for Yarragadee, Arequipa, and Monument Peak (Drożdżewski and Sośnica, 2017).*

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Joint Study Group 0.l5: Regional geoid/quasi-geoid modelling – Theoretical framework for the sub-centimetre accuracy

Chair: *Jianliang Huang (Canada)*
Vice Chair: *Yan Ming Wang (USA)*

Members

- *Riccardo Barzaghi (Italy)*
- *Heiner Denker (Germany)*
- *Will Featherstone (Australia)*
- *René Forsberg (Denmark)*
- *Christian Gerlach (Germany)*
- *Christian Hirt (Germany)*
- *Urs Marti (Switzerland)*
- *Petr Vaníček (Canada)*
- *Yan Ming Wang (USA)*

Activities during the period 2015-2017

Activities are organized and reported by components of the JSG objectives as follows:

<u>Spectral combination of different types of gravity data</u>

Foroughi et al. (2015a) addressed the question of how a global gravity field model may best be used to fill spaces void of observed gravity data to arrive at a relatively homogeneous data coverage. Foroughi (2016b) formulated and came up with the best combination of a degree and order of reference field and integration cap size in the Stokes-Helmert approach to regional geoid computation. Also a new computational algorithm was tested. The resulting geoid for the Auvergne region is improved by 0.5 cm when compared to the GPS/levelling geoidal heights.

Due to progress in space and airborne technologies, more high quality gravity field related data are collected. These data are often complementary in their spectral contents, thus the challenge of geoid determination today is to combine multiple data types according to their error characteristics. Wang et al. (2016) discussed two methods of combination: the spectral combination and the least-squares collocation with emphasis on the first. The principle of spectral combination is as simple as a weighted spectral mean. The difficulty is to estimate the spectral weights for each data set realistically. This method establishes a mathematical framework for the combination of multiple types of gravity data for geoid determination. They also showed that the standard remove-compute-restore scheme is a special case of this method. The spectral combination method was applied for satellite, airborne and terrestrial gravity data in the US NGS's GSVS11 demonstrating the contribution of GRAV-D for the middle wavelength components of the gravity field (Jiang and Wang 2016).

Gerlach and Ophaug (2017) have derived combined geoid solutions from state-of-the-art satellite only models (based on relase-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. The latter were chosen, because they were used earlier in our study area Norway; 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. The error estimates (error degree variances) for the satellite data were derived from the formal error description of the DIR and GOCO models, respectively (classical error degree variances were rescaled to fit the local amplitude of the error variance derived from an m-block approximation of the full error variance-covariance matrix). Error estimates of the terrestrial data are based on published correlated error models. They compared the combined solutions as well as existing regional geoid models to GNSS-levelling data to derive empirical error estimates. While comparison with older geoid models shows the general improvement brought by the satellite missions GRACE and GOCE (improving the overall RMS fit from around 8 cm before GRACE and GOCE, to currently around 3 cm), their own weighting schemas allow to give an estimate of the expected mean error of the terrestrial data. They could show that the dataset used, on average, is probably less accurate than the one used for the derivation of the European Gravimetric Quasigeoid EGG2015 (again on average). While the latter gives the best overall fit to independent data assuming an average error standard deviation of 0.2 mGal for the terrestrial data, they found that the error standard deviation of the Norwegian data set seems to be in the order of 2 mGal. Later comparisons with the latest version of the Nordic geoid NKG2015 showed a decrease of the error budget (down from around 3 cm to 2.5 cm) which leads to the conclusion that the Norwegian dataset has been improved recently. This latest dataset was not available for the investigations. Comparison of empirical and formal error budgets indicate that the overall error budget derived from comparison with GNSS-levelling is probably dominated by errors in the levelling data. Further investigations on the different error sources will be performed in the next study period.

Gravity reduction

Foroughi et al. (2015b) investigated the fit along the boundaries between downward continued gravity anomalies on the geoid obtained separately for one degree squares. The fit was assessed by statistical means and found to be rather good. Sheng et al. (2015) investigated the differences between the downward continued gravity anomalies in Helmert's and the NT spaces. They found out that the differences were inexplicably large and realized that these large differences were caused by insufficiently accurate evaluation of the FZ contribution in the case of the NT space. Consequently, the use of the Helmert space should be preferred. Kingdon and Vaníček (2015) formulated two different algorithms for determining gravity anomalies on the geoid in regions containing both positive and negative heights using simultaneous downward and upward continuation. It was found that both algorithms give comparable results. This research is to be continued when good real data become available. Kingdon et al. (2015) studied least-squares downward continuation of gravity anomalies in Helmert's space, introducing the concept and showing some sample applications. Foroughi et al. (2016a) further analysed the sensitivity of Poisson's integral to the location of points both on topography and on the geoid. Foroughi et al. (2016c) also studied three different scenarios for point location on topography – on a regular grid, combination of regular grid and scattered points and scattered points alone. 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.

Sheng et al. (2016a. b) investigated how rigorously to transform gravity potential harmonic series into Helmert's space, after discovering that the development in [Vaníček P, Najafi M, Martinec Z, Harrie L, Sjöberg LE, 1996. Higher-order reference field in the generalized

Stokes-Helmert scheme for geoid computation. *Journal of Geodesy* 70 (3): 176-182] was not correct. The changes (improvements) compared to the standard technique reach 24 cm in range and 1 cm in standard deviation (globally). Lin and Denker (2016) investigated the computation of topographic and atmospheric effects with tesseroids.

Applications of new tools such as the radial basis functions

It is known from literature that different methods for gravity field modelling – specifically Stokes's integration, least-squares collocation or representation in spherical splines – are equivalent in global applications. The application of one of the methods in a specific regional application may be a matter of an evaluation of pros and cons of the different methods, or a matter of availability of software tools, or experience of the user. As the application of spherical radial basis functions got increased interest in recent years, it is interesting to review the equivalence of this approach with the classical Stokes and collocation methods. Ophaug and Gerlach (2017) investigated the equivalence of these three methods in regional applications both from a theoretical as well as from a numerical point of view. They have used a set of synthetic gravity anomalies to perform regional geoid computation based on Stokes integration, collocation and spherical splines in an error free closed-loop simulation. Input data was a 5'x5' grid of gravity anomalies derived from EGM2008 to full resolution. Computations were performed for two test areas with smooth and moderately rough gravity field characteristics. They found that all methods agree on the sub-millimetre to millimetre level, where the largest deviations are due to discretization errors of Stokes integral equation. In general collocation provides the best results, but the spline representation is almost equivalent. They did not go into evaluation of pros and cons of the methods, but only investigated the numerical equivalence. However, it would be interesting to carry out further research on this in order to provide guidelines on which method may be the preferred one in a special situation, considering e.g. numerical burden. They did also not apply the methods to real datasets. This again is left to future research.

In the meantime, Lin et al. (2015, 2016) investigated the regional gravity field modelling based on a two-step point mass method with free depth, and compared it with the Least-Squares Collocation method. Numerical tests demonstrated close solutions between the two methods.

Independent validation of geoid/quasi-geoid models

The tilt of coastal mean sea level with respect to an equipotential surface can be estimated using two fundamentally different approaches. The geodetic approach is based on tide gauge and GPS observations, and a model of the geoid. The ocean approach uses a high-resolution, dynamically based ocean model to estimate mean dynamic topography. Along the Pacific coast of North America the two approaches give similar large-scale profiles with a minimum at about 408N and a maximum in the northern part of the Gulf of Alaska. Along the Pacific coast of Japan the geodetically determined coastal sea levels indicate an eastward drop of about 20 cm along the south coast and a further northward drop across Tsugaru Strait. Both of these features are reproduced by the ocean models (Lin et al. 2015).

Huang, J. and M. Véronneau (2015) assessed the GRACE and GOCE release 5 (R5) global geopotential models (GGM) using GPS-Levelling data, astronomic deflections of the vertical and terrestrial gravity data in Canada. The accuracy of the GOCE R5 models was estimated to be better than 4-5 cm up to spherical harmonic degree ~200. The traditional astronomic deflections appeared not accurate enough to measure improvements in the GOCE R5 models with respect to the GOCE R4 models. The analysis inferred that the GOCE contribution in EIGEN-6C4 is more accurate than the corresponding wavelength components in EGM2008.

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. They will be further utilised for the computation of astronomical quasigeoid profiles to provide an independent check on gravimetric quasigeoid models and GPS-levelling data. This is the first in Australia and indeed the Southern Hemisphere that has been acquired with modern digital astronomical instrumentation. The deflection data set will be made freely available to the geodetic community, e.g., for testing of future quasi/geoid or global geopotential models. This project was devised and led by Christian Hirt, and received financial support by the German Academic Exchange Service (DAAD) and Universities Australia. Local assistance came from Will Featherstone and Todd Lyon (Perth) and from C.R. Kennedy.

Anomalous topographic mass density effect on the geoid model

Forgoughi et al. (2015c) investigated whether a publicly available mid-scale geological map can be used to improve the geoid computed by the Stokes-Helmert process in Auvergne. Even though the improvement was not overwhelming, they showed a systematic improvement after applying the laterally varying topo-density variation effects. Tavakoli et al. (2016) did a study of an application of Kouba’s refined form of Poisson’s partial differential equation of gravity potential to the problem of topographical density determination.

Data type, distribution and quality requirements

Klu et al. (2015) did a test for the Stokes-Helmert technique of geoid computation with real, rather sparse data. Results confirmed that a relatively good geoid can be obtained even with sparse data.

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

Chair: *Robert Tenzer (China)*

Members

- *Lars Sjöberg, Sweden*
- *Mohammad Bagherbandi, Sweden*
- *Carla Braitenberg, Italy*
- *Mirko Reguzzoni, Italy*
- *Xiaodong Song, USA*

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Joint Study Group 0.l7: Multi-GNSS theory and algorithms

Chair: *Amir Khodabandeh (Australia)*

Members

- *Peter J.G. Teunissen (Australia)*
- *Pawel Wielgosz (Poland)*
- *Bofeng Li (China)*
- *Simon Banville (Canada)*
- *Nobuaki Kubo (Japan)*
- *Ali Reza Amiri-Simkooei (Iran)*
- *Gabriele Giorgi (Germany)*
- *Thalia Nikolaidou (Canada)*
- *Robert Odolinski (New Zealand)*

Activities and publications during the period 2015-2017

This report presents an overview of activities undertaken towards the objectives of the ICCT Joint Study Group 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.

JSG Members' Activities

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 (Figure 0.17). 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.

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 the 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 %.

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.

Group Discussion

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).

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

Chair: *Sten Claessens (Australia)*

Members

- *Hussein Abd-Elmotaal (Egypt)*
- *Oleh Abrykosov (Germany)*
- *Blažej Bucha (Slovakia)*
- *Toshio Fukushima (Japan)*
- *Thomas Grombein (Germany)*
- *Christian Gruber (Germany)*
- *Eliška Hamáčková (Czech Republic)*
- *Christian Hirt (Germany)*
- *Christopher Jekeli (USA)*
- *Otakar Nesvadba (Czech Republic)*
- *Moritz Rexer (Germany)*
- *Josef Sebera (Italy)*
- *Kurt Seitz (Germany)*

Activities and publications during the period 2015-2017

Activities by members of the joint study group on high-resolution harmonic analysis and synthesis of potential fields have resulted in many new advances, and significant progress has been made towards many of the group's objectives. The main results over the period 2015-2017 are summarised below.

<u>Algorithms and software for ultra-high degree spherical and spheroidal harmonic analysis and synthesis</u>

A major challenge in the creation of efficient algorithms for ultra-high degree spherical and spheroidal harmonic analysis and synthesis is the precise and stable computation of associated Legendre functions (ALFs) of the first and second kind (or ratios thereof), plus its derivatives and integrals.

Fukushima (2015) reviews the X-number formulation for the computation of point values, derivatives, and integrals of ALFs of the first kind and point values and derivatives of oblate spheroidal harmonics of the second kind. The X-number formulation resolves the underflow problem in the computation of point values of ALFs of the first kind up to and beyond degree 216,000. Computation can be accelerated by implementation of a dynamic switch from the X-number to the ordinary floating-point number during recursions, and by application of folded parallel computation. Fukushima (2017) addresses the degradation of precision near the poles in the computation of ALFs by using a rectangular rotation of the spherical harmonic expansion to move the polar singularity to the equator.

Gruber and Abrykosov (2016) have focused on the applicability of transformations between spherical harmonic expansions and bivariate Fourier series to the computation of ALFs. In this approach, the ALFs are expanded in coefficients of harmonic functions. Fast and stable algorithms have been developed and evaluated. With this tool future high resolution gravity field models can be stably synthesised or analysed in regular grid representations, and using reduced or geodetic latitudes as well. Fukushima (submitted) also present an algorithm based on the Fourier series approach, using a three-term forward recurrence formula for the computation of the rectangle value of the Wigner d-function. The method stably provides accurate results for even extremely high degree and order ($\sim 10^9$).

A Fortran95 software extension for ultra-high degree surface harmonic analysis was developed and released to the public by Rexer and Hirt (2015a). The software combines the Gauss-Legendre and Driscoll-Healy quadrature from the SHTOOLS software suite (www.shtools.org) with the Fukushima X-number algorithms for stable computation of ultra-high degree ALFs, and offers parallel processing capability. The new software can be considered an important “building block” for ultra-high degree gravity forward modelling with spectral techniques.

Nesvadba and Holota (2015) have developed an efficient streaming-parallel algorithm for the computation of oblate spheroidal harmonic functions and their derivatives. They utilise an Open Computing Language (OpenCL) implementation on a general-purpose graphic processing unit (GPGPU). The resulting algorithm is significantly more efficient than the “traditional” hypergeometric series approach on a CPU. They have also developed various techniques for numerical treatment of series of ALFs (first and second kind) of imaginary argument, some of which are presented in Holota and Nesvadba (2015).

Sebera et al. (2016a) present a novel ellipsoidal approach for updating high-resolution models over the oceans with new gridded data. This was done in spheroidal approximation to spheroidal degree 4430 (with Gauss-Legendre quadrature employed). This work includes a slight modification of the Legendre functions of the second kind in the Jekeli renormalisation, now allowing grid-wise calculations above degree 10,000. Sebera et al. (2016b) study the spheroidal approximation of both the oblate and prolate bodies in case of two asteroids. For the prolate case, the relations between curvilinear and Cartesian partial derivatives up to the second order are provided.

A new analytical method for solid spherical harmonic analysis from data on a spheroid is presented in Claessens (2016). The method uses a transformation between surface and solid spherical harmonic coefficients and is compared to an alternative method that uses the Hotine-Jekeli transformation with Sebera modification. Both methods achieve sub-micrometre precision in terms of height anomalies for a model to degree 2239. However, it was also shown that high and ultra-high harmonic expansions exhibit significant differences when a different type of latitude (geocentric or reduced) is used in the input grid.

A relatively new topic is the harmonic analysis and synthesis of gravitational curvatures (third-order gradients of the gravitational potential). The conventional spherical harmonic expansions of the gravitational curvatures in a local north-oriented reference frame depend on the first-, second- and third-order derivatives of the associated Legendre functions, and some of these expansions contain singular terms at the poles. Hamáčková et al. (2016) have developed new non-singular expressions for spherical harmonic synthesis of gravitational curvatures by transforming the conventional series to new simpler and non-singular forms based on relations between ALFs and their derivatives.

Bucha and Hirt have developed a new method for fast spherical harmonic synthesis at the topographic surface (not yet published). The currently used gradient approach does not work reliably for very high orders of the Taylor series (i.e., beyond the order of 50) and for extremely rough signals. In places where the gravity signal highly oscillates a high maximum harmonic degree of the expansion in a combination with a high Taylor series order is needed. The new method is based on an interpolation in the radial direction.

Fukushima (2016) presents harmonic expansions of external gravitational fields for ring-like objects, which cannot satisfactorily be expanded using spherical, spheroidal, or ellipsoidal harmonics. Instead, an expansion in terms of zonal toroidal harmonics is derived.

Convergence vs. divergence in spherical and spheroidal harmonic series

Often, spherical harmonic series expansions are evaluated inside the sphere encompassing all masses (Brillouin sphere), e.g., to predict the gravity field near the surface. Inside the Brillouin sphere, however, the external potential series may converge or may diverge, that is, produce invalid values. This holds similarly for spheroidal or ellipsoidal harmonic series expansions evaluated inside the Brillouin spheroid or ellipsoid.

Hu and Jekeli (2015) study the possible divergence effects and amplified omission errors in spherical, spheroidal, and ellipsoidal harmonic series for gravitational modelling of small moderately irregular bodies. Numerical tests for the Martian moons Phobos and Deimos show significant divergence in spherical and spheroidal harmonics already at low degrees, but less distinct divergence behaviour in ellipsoidal harmonics.

For Earth's topographic potential to degree-2160, convergence is often assumed and can indeed be taken for granted when synthesising gravity functionals at the Earth's surface (Hirt et al. 2016a), although there is evidence for minor, but measurable divergence in the spherical harmonic series at ultra-high degree. This finding may be important for the development of future ultra-high-resolution gravity fields with spectral techniques. However, the situation is entirely different for Earth's Moon due to its much rougher undulating surface and range in topographic elevation. A case study for the Moon (Hirt and Kuhn 2017) has investigated divergence effects in high-degree spherical harmonic series of the topographic potential by comparisons against accurate numerical integration. As key results, gravity on the lunar surface can be synthesised from the topographic potential coefficients to degree ~180 without divergence. Opposed to this, high-degree series (e.g., degree 1080 or degree 2160) produce invalid values when gravity functionals are synthesised at the rough lunar surface, see Figure 17. As such, the new investigations exemplify the problem of series convergence vs. divergence for the Moon and show that the Earth case is much less affected by divergence, presumably due to the overall smoother topography. For rugged planetary bodies, the findings necessitate the development or application of alternative techniques (e.g., combinations with interior potentials) to generate spectral gravity field models that are less affected by divergence.

Bucha has worked on an as yet unpublished alternative approach that would deliver a spherical harmonic series providing reliable results even at the topography. The approach is based on an iterative downward continuation of data from the topographic surface to the Bjerhammar sphere. The input data are given by the Newtonian integration in the spatial domain which is free of the divergence issue. From these data, a reliable spherical harmonic series can be obtained via downward continuation.

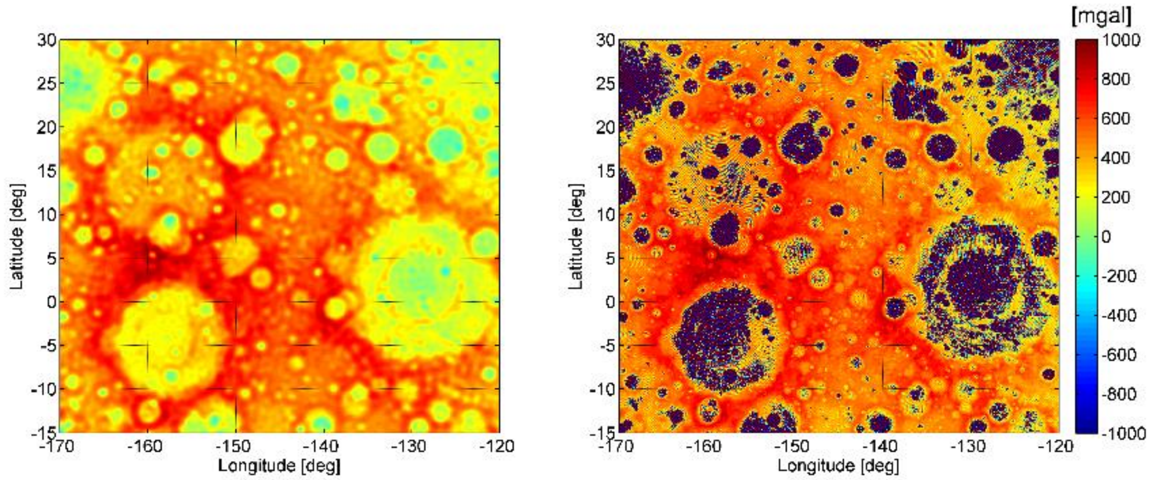

Figure 17. *Gravity implied by topography over the Far-side Highlands of the Moon, computed with spectral techniques. Left: to harmonic degree 360, Right: to harmonic degree 2160. The right panel shows invalid gravity values inside the craters, occurring as a consequence of series divergence in the spectral technique at high degrees over rugged terrain.*

<u>High-resolution spherical and spheroidal harmonic models and degree variance models</u>

High-resolution harmonic models are used for the description of gravitational potential fields, but also for the description of topographic or topographic-isostatic potential fields obtained through gravity forward modelling. Earth's near-surface masses are generally considered to be the main contributor to short-scale gravity field signals. High-resolution and up-to-date models of topography, water and ice masses are therefore important for detailed gravity forward modelling, and these have also been represented as harmonic models.

Hirt and Rexer (2015) have developed and publicly released the Earth2014 topography product compilation which describes Earth's shape, topography, water, bedrock and ice-sheets with 1 arc-min resolution, see Figure 18. The Earth2014 models improve over previous 1-arcmin compilation such as ETOPO due to the inclusion of newer ice and bathymetry data sets. The grids were expanded into ultra-high degree spherical harmonic coefficients to degree and order 10,800. The data can be used, e.g., for testing of ultra-high degree synthesis and analysis software, and deployed in gravity forward modelling with spectral methods (series expansions) and spatial methods (numerical integration). The Earth2014 is distributed via IAG's IDEMS elevation model service and ddfe.curtin.edu.au/models. In addition, Rexer and Hirt (2015a) harmonically analyse the constituents of planetary topographies (Earth, Moon, Mars) to ultra-high degree of up to ~46,000, see Figure 19.

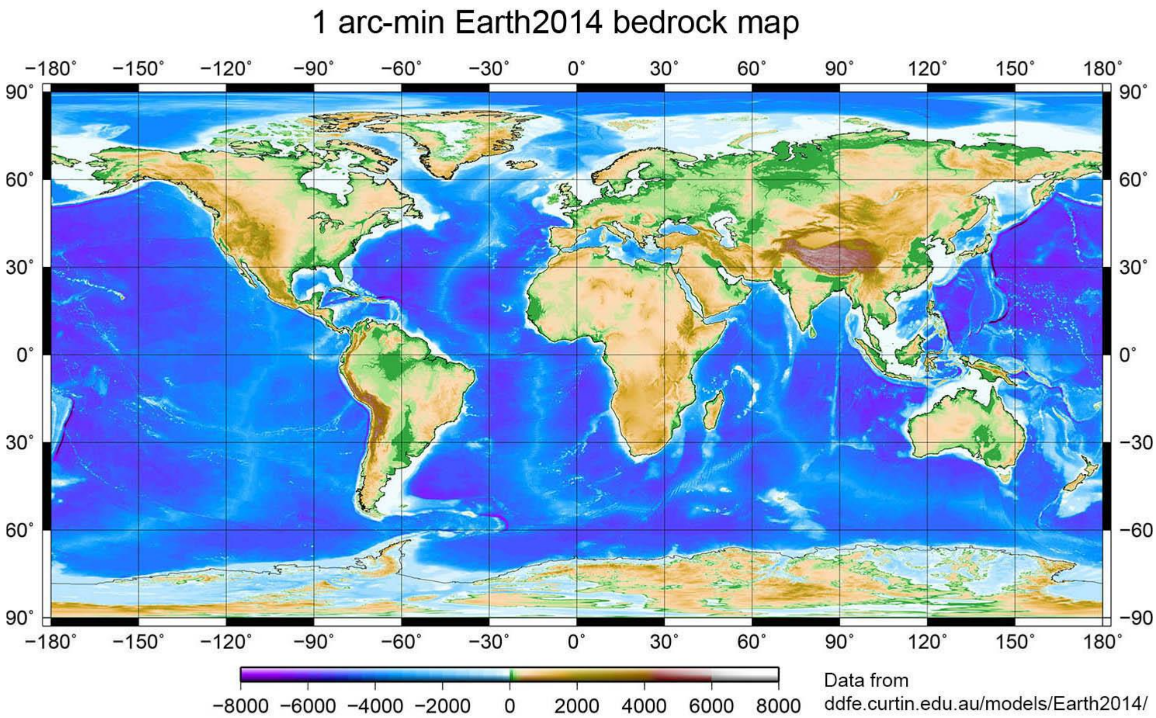

Figure 18. *Example of Earth2014 data layers – 1 arc-min resolution bedrock topography*

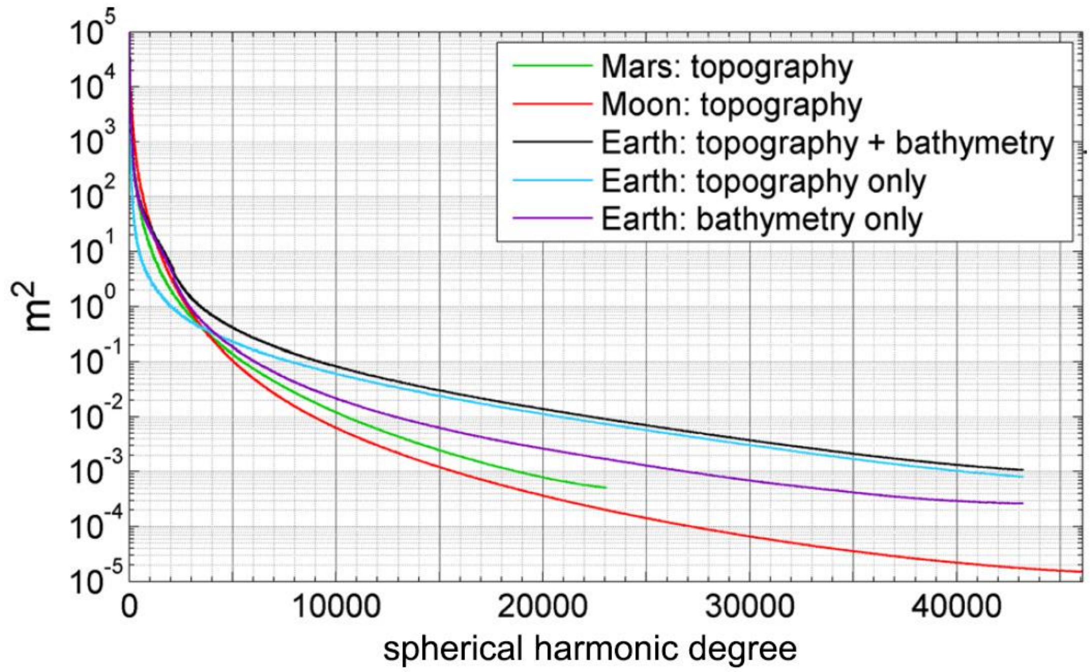

Figure 19. *Degree variance models for planetary topography models, computed from surface harmonic coefficients up to degree and order ~46,000*

A new technique for spectral-domain gravity forward modelling was introduced by Rexer et al. (2016). The new approach allows rigorous modelling of the topographic potential generated by multiple, arbitrarily (star)-shaped mass-layers relative to a mass-ellipsoid in spherical harmonics. Before this work, the potential of multiple mass-layers was forward-modelled relative to a mass-sphere or the potential of a single-layer was forward-modelled relative to a mass-ellipsoid, but no approach existed thus far that merged both techniques. The approach was applied in Rexer et al. (2016) to produce dV_ELL_Earth2014 model that describes the topographic potential of the Earth2014 model to 5-arcmin resolution (or spherical harmonic degree 2,190). The dV_ELL_Earth2014 model is distributed via IAG's ICGEM service. Rexer (2017) and Rexer et al. (2017) applied the methods to model the Earth2014 potential of topography, ice- and water-masses to degree 5400 without truncations or approximations.

Grombein et al. (2016) have also used the Earth2014 model to generate a high-resolution spherical harmonic representation of the Earth's topographic potential to degree 2190 (RWI_TOPO_2015). This study performs the gravity forward modelling in the space domain, followed by a least-squares spherical harmonic analysis. The RWI_TOPO_2015 model is also distributed via IAG's ICGEM service.

Abd-Elmotaal and Kühtreiber (2015) have developed a new algorithm to compute the ultra-high harmonic coefficients of the topographic-isostatic masses on the surface of the ellipsoid. The formulas are rigorous. Numerical studies reveal that the approach works well. Abd-Elmotaal et al. (in prep) compare this method with the method by Grombein et al. (2016). This study shows some differences in the frequency domain between the two tested approaches, but the differences in the space domain are much smaller.

The German GeoForschungsZentrum (GFZ) is currently developing a high-resolution terrain model that uses the advanced harmonic analysis developed by Gruber and Abrykosov (2016).

Some studies have used high-resolution harmonic models of the gravitational potential in combination with forward modelling to derive an accurate model of the gravity field in a local or regional area. Hirt et al. (2016b) explore high-degree spectral forward modelling to improve the gravity field over Antarctica. The Bedmap2 data set contained in the Earth2014 topography model was used to refine the gravity field over Antarctica beyond the resolution of current GRACE and GOCE gravity fields. The Earth2014 data set was used as input data to forward-model the implied gravity field in ellipsoidal approximation (i.e., field-generating masses arranged relative to an ellipsoid) and spherical harmonics to degree 2190. A combination technique based on normal-equations was applied to merge the forward model with gravity from the GRACE and GOCE missions. The resulting model (SatGravRET2014) was validated with gravity observations from the IAG Subcommission 2.4 "Gravity and Geoid in Antarctica" (AntGG) database. The work demonstrated that spectral forward modelling is capable of filling some gaps in short-scale gravity knowledge over Antarctica contained in current global geopotential models such as EGM2008.

Bucha et al. (2016) have developed a high-resolution regional gravity field over the Slovak Republic (Central Europe) via a combined approach using spherical harmonics (to degree 2190), band-limited spherical radial basis functions (the Shannon SRBF, to degree 21,600) and RTM technique. The model is developed from a dense terrestrial gravity database (3 – 6 stations per km^2), which allowed to model the gravity field up to harmonic degree 21,600. The model is validated against independent height anomalies, surface gravity data, deflections of the vertical and terrestrial vertical gravity gradients. This paper presents an alternative approach to the common spherical harmonic gravity modelling. It is especially useful when modelling the gravity field on a regional scale and up to an ultra-high spatial resolution. Spherical harmonic modelling up to degree 21,600 requires the determination of more than 466 million coefficients which cannot be done at the present time by the least-squares technique with the full normal equation matrix. On the other hand, in regional gravity field modelling via SRBFs, only about 78,000 coefficients had to be estimated, which is not difficult to achieve even with the full normal equation matrix.

Another example of a high-resolution harmonic models are surface harmonic expansions of specific gravitational functionals. Claessens and Hirt (2015) have derived a surface spherical harmonic expansion of gravity anomalies with respect to a geodetic reference ellipsoid. This is based on a rigorous transformation of solid spherical harmonic coefficients of a global gravity model. Contrary to earlier methods, it does not rely on approximations to the order of the second or third power of the eccentricity of the ellipsoid, which are shown to be insufficient at high and ultra-high degrees.

Finally, a spectral analysis of the GGMplus gravity maps to ultra-high resolution (equivalent to degree 90,000) was performed by Rexer and Hirt (2015b). Using 2D-DFT methods, a new degree variance model was developed that describes the decay of gravity signals over Earth's land areas to ~250 m resolution, see Figure 20. As improvement to previous works, the new degree variance model is supported through topography-implied gravity to degree ~90,000 [often, previous degree variance models were data-supported only to 100 or 10 km spatial scales, so subject to extrapolation errors when used to predict the short-scale signal characteristics of the gravity field]. The degree variance model developed may serve as a reference in comparisons with future ultra-high degree series expansions of the gravitational field. Also, it could be shown that the effect of the ellipsoidal or spherical arrangement of the field-generating masses on the power spectra is becoming more significant the shorter the spatial scale, so deserves due attention when applying degree variance models, e.g., to compute omission errors.

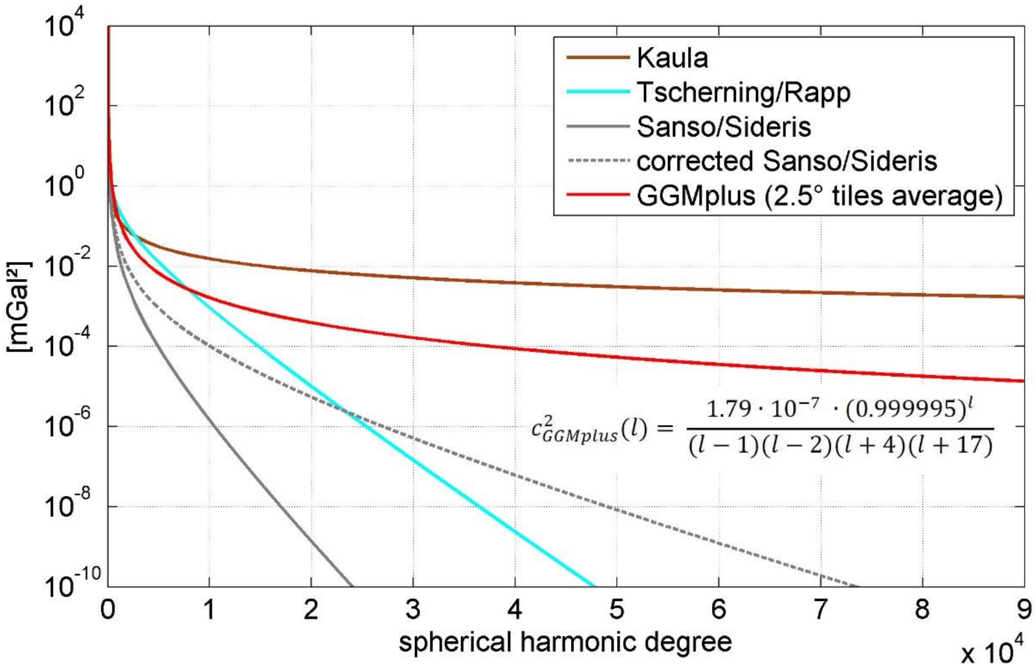

Figure 20. *Degree variance models from GGMplus (red curve) in comparison with other degree variance models*

<u>Applications of high-resolution harmonic models</u>

Recent advances in high-resolution harmonic modelling of potential fields have successfully been used to gain important insights and results.

One example is the computation of spherical harmonic Bouguer gravity anomalies, a frequently used approach used in planetary sciences, which is now becoming more popular with the Earth gravity modelling community. The Bouguer gravity is obtained in the spectral domain by subtracting the coefficients of the topographic potential from those of the observed potential (e.g., GOCE, EGM2008 or EIGEN-6C models). Hirt et al. (2016a) focus on the validation of the spectral-domain forward-modelling technique used to generate the harmonic coefficients of the topographic potential at 5 arc-min resolution. A full-scale numerical integration technique (Newtonian integrator by Curtin University) was applied in the space-domain to deliver the topographic potential independently from the spectral approach. It is known that the gravity field obtained through numerical integration contains gravity signals at scales much finer than the resolution of the field-generating topography. To ensure spectral consistency between the spectral-domain and spatial-domain solutions, the gravity field generated by the degree-2,160 topography was modelled to ultra-high degree of 21,600. The study revealed micro-Gal consistency between the two modelling techniques over most of the Earth's surface, see Figure 21.

Another example is the insight gained in the understanding of the correlation between the gravitational and topographic potential at small spatial scales, as the importance of the parameterisation and geometry applied has been revealed. When spectral techniques are used to model Earth's gravity field, parameterisations are possible in terms of spherical, spheroidal or ellipsoidal harmonics. On the other hand, when gravity forward techniques are applied, the field-generating masses can be arranged relative to a mass-sphere or mass-ellipsoid of revolution. The first case is sometimes denoted as spherical approximation level and the second case as ellipsoidal approximation level. In practice, approximation levels and parameterisations are often mixed, e.g., EGM2008 being a spherical harmonic representation using ellipsoidal approximation levels. Hirt et al. (2017) investigate how correlation measures – e.g., correlation coefficients or reduction rates – that are often formed between geopotential models (e.g., EGM2008) and topographic potential models (e.g., dV_ELL_Earth2014) depend on the parameterisation and approximation level. When the EGM2008 SHCs (spherical harmonic coefficients) are correlated with SHCs of the topographic potential model in ellipsoidal approximation, the resulting correlation measures have been found biased over most of the spectrum. In the previous example, the correlation between EGM2008 and topographic potential reaches a maximum near degree ~1,000, though it should be maximum near the full model resolution (near degree 2,160). The biases can be avoided by using either SHCs together with spherical approximation or EHCs (ellipsoidal harmonic coefficients) with ellipsoidal approximation (Figure 6). Then, maximum correlation is indicated near the shortest scales resolved by the global gravity field model (Hirt et al. 2017). While this may necessitate coefficient transformations prior to the correlation analysis, wrong or ambiguous conclusions regarding the model properties and gravity field composition can be avoided.

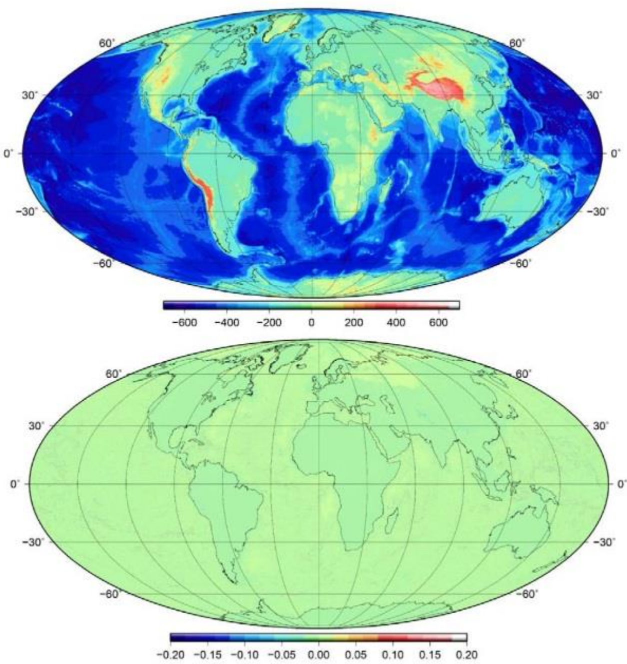

Figure 21 Top*: Gravity implied by Earth's topography to degree-2160, computed with numerical integration. Bottom: Differences between gravity implied by topography from numerical integration and spectral modelling to degree 21,600. Unit in mGal.*

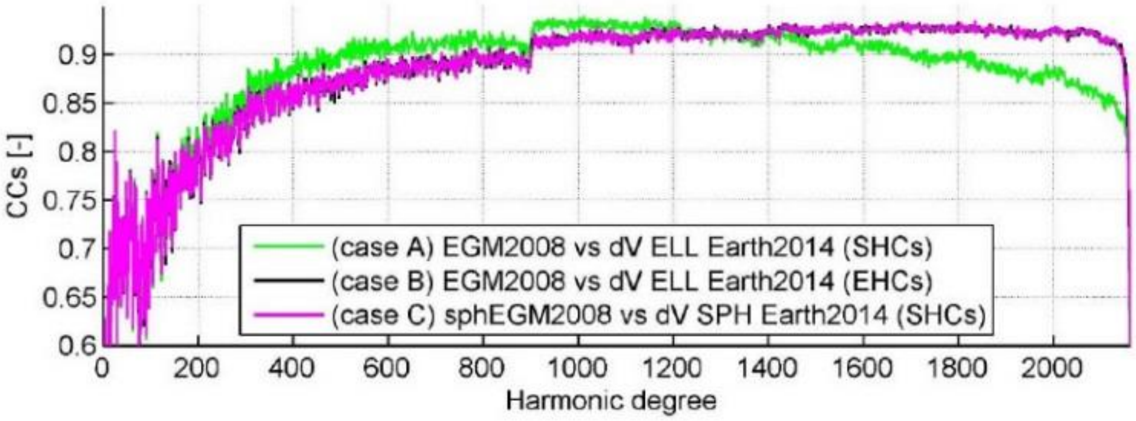

Figure 22*. Correlation between Earth's observed and topographic potential as a function of the harmonic degree. The green curve is biased, while the black and pink curves give more realistic information on the degree correlation (for details see Hirt et al. 2017).*

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Joint Study Group 0.l9: Time series analysis in geodesy

Chair: *Wiesław Kosek*

Members

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- *Jan Vondrák (Czech Republic)*
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- *Michel Van Camp (Belgium)*
- *Hans Neuner (Germany)*
- *Xavier Collilieux (France)*
- *Anna Kłos (Poland)*

Activities and publications during the period 2015-2017

The following activities were undertaken within JSG 0.19 Time series analysis in geodesy during the period 2015-2017.

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 sub-seasonal oscillations in altimetric sea level anomaly (SLA) data. These oscillations are mostly irregular and cause an increase of prediction errors of the SLA data. The SLA data prediction errors for a few weeks in the future are usually considerable in geographic regions where amplitude maxima of the broadband annual oscillation and other shorter period oscillations are the largest (Kosek et al., 2015).

Time frequency analysis by the 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 from a few days to few weeks in the future in show wideband signals corresponding to chaotic short period oscillations and to the residual prograde Chandler and annual oscillations (Kosek and Kalarus, 2017; Brzezinski et al., 2016).

The FTBPF+HT and NMWT were used to compute the amplitude coherence functions between two real-valued time series e.g. length of day and some chosen time series representing solar activity. This function is defined as the correlation coefficient between amplitude variations of oscillations in the two series as a function of their periods (Kosek and Popiński, 2017).

A comparison of predictive skills of two Polish systems designed for sea level change (Prognocean and Prognocean Plus) with the EU-recognized MyOcean solution was performed (Swierczynska et al., 2016). The system uses satellite altimetric time series. Prognocean and Prognocean Plus are based on the data-based prediction methods which use deterministic and deterministic-stochastic approaches. It has been found that Prognocean Plus reveals smaller prediction errors than MyOcean does, however, the variability is better resolved by the latter system.

A new method for estimating oceanic depth vs. oceanic age in geologic time has been elaborated. The method is based on modelling bathymetric curve and basic relationship between age and area. For relatively long periods, the model predicts depth as a function of age with comparable accuracy to already existing models (Niedzielski et al., 2016).

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

A non-parametric wavelet decomposition was employed to investigate the non-linear motion of GNSS stations (Bogusz, 2015).

Bogusz et al. (2015a) focused on the quasi-annual changes in GNSS-derived time series from PPP solution obtained by JPL (Jet Propulsion Laboratory) from more than 300 globally distributed IGS (International GNSS Service) stations. They divided all stations into clusters characterized by similar quasi-annual curve estimated with wavelet decomposition. They concluded that the maximum vertical amplitude was at the level of 14 mm with the minimum equal to 13 mm, giving the peak-to-peak position changes up to 27 mm.

The common mode errors (CME) were estimated for a set of ASG-EUPOS permanent GPS stations with the stacking approach. The reduction of standard deviation estimated for the GPS position time series was noticed when CME was removed (Bogusz et al. 2015b).

Gruszczynski et al. (2016) estimated the CME using Principal Component Analysis (PCA) and removed it from the GPS position time series. An average reduction in velocity uncertainty of 0.2 mm/year, with a maximum reduction of 0.8 mm/year was noticed when CME was removed.

Bogusz and Klos (2016) proposed to model the seasonal part of the GPS position time series including all periodicities from 1st to 9th of tropical year, including also residual Chandler period and fortnightly frequencies. They found that this assumption of seasonal signals helped to improve the velocity uncertainty of 56% comparing to the classical approach of annual plus semi-annual curves.

Bogusz et al. (2016) investigated the long-range dependence with Hurst exponent and detrended fluctuation analysis to be present in the GPS data.

Gruszczynska et al. (2016) used 18 GPS stations from the area of central Europe and modelled the time-varying seasonal signal with Singular Spectrum Analysis (SSA). They found that the SSA-derived curves are more correlated with original data than Least-Squares Estimated-curves, proving that the amplitude of seasonal curves is time-variable.
The common seasonal signal for a set of European stations using Multichannel Singular Spectrum Analysis (MSSA) was extracted. It was concluded that the MSSA-curves contain

only time-varying and common seasonal signal and leave the station-specific part, local phenomena and power-law noise intact (Gruszczynska et al., 2017).

The character of noise for a set of 115 European GPS stations which contributed to the newest release of the International Terrestrial Reference Frame (ITRF), i.e., ITRF2014 with Maximum Likelihood Estimation (MLE) was estimated (Klos and Bogusz, 2017). It was found that stations situated in the Central and Northern Europe are characterized by the spectral index between flicker and random walk noise, while stations in Southern and Western Europe: between white and flicker noise.

Different noise models for the EPN (EUREF Permanent Network) GPS stations were compared. It was found that a combination of white plus power-law noise model is the preferred noise model for weekly time series (Klos et al., 2015a).

Klos et al. (2016) used 42 stations from the IGS network from Europe. They showed that the coloured noise between white and flicker noise with the amplitudes between 3 to 6 mm/year$^{\kappa/4}$ for horizontal components and between 6 to 15 mm/year$^{\kappa/4}$ for the vertical ones is the best to describe the stochastic part of data. They proved that the amplitudes and spectral indices of noise are reduced after performing a spatio-temporal filtering.

Klos et al. (2015b) examined data from 115 permanent GPS stations. They estimated the values of skewness and kurtosis and found that these values clearly indicate the discrepancies between the assumed normality of the GPS time series and the reality, mainly due to stochastic and/or deterministic parts that are still present in the data.

Klos et al. (2015c) examined the stochastic properties of 18 Polish permanent GPS stations that belong to the EPN (EUREF Permanent Network) using Maximum Likelihood Estimation (MLE) to indicate the influence of monuments on the character of GPS data.

Klos et al. (2015d) showed how important the pre-analysis of data is, when one aims at the most reliable estimates.

Klos et al. (2017) employed 376 permanent IGS stations, derived as the official contribution to the ITRF2014. They modelled the seasonal signals in environmental models using the Improved Singular Spectrum Analysis (ISSA) approach and subtracted it from GPS vertical time series to leave the noise character of the time series intact.

Kowalczyk and Bogusz (2017) described an idea of determining the height changes with a use of Vertical Switching Edge Detection (VSED) algorithm estimated from PPP solution provided by NGL (Nevada Geodetic Laboratory) for more than 50 permanent stations located in Latvia, Lithuania and northeastern Poland.

A summary of research activities concerning theoretical geodesy performed during 2011-2014 was presented by Borkowski and Kosek (2015).

Hourly time series of Earth rotation parameters from VLBI observations in a single-session strategy were determined. Then, the S1 (period of 24 h) 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 behavior of the polar motion and use it successfully for prediction (Kucak et al., 2016).

Abbondanza et al. (2015) estimated the uncertainty in the observed positions of geodetic stations by applying the three-corner-hat method to second-order statistics computed from time series of the observed positions of geodetic stations located at the same site.

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 non-seasonal 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 mutually compared. 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).

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 is considered, where the observed function values are corrupted by multiplicative errors (errors in amplitude and phase) as well as additive noise (Popiński, 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 analyzed the signature of climate-induced inter-annual 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.

PICO G1.2 Sessions titled "Mathematical methods for the analysis of potential field data and geodetic time series" were organized at the European Geosciences Union General Assemblies in 2015, 2016 and 2017 in Vienna, Austria. A number of about 50 contributions in total were presented at these sessions.

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Joint Study Group 0.20: Space weather and ionosphere

Chair: *Klaus Börger (Germany)*

Members

- *Michael Schmidt (Germany)*
- *Jürgen Matzka (Germany)*
- *Mahmut Onur Karslioglu (Turkey)*
- *Eren Erdogan(Germany)*
- *Barbara Görres (Germany)*
- *Ehsan Forootan (United Kingdom)*
- *Johannes Hinrichs (Germany)*
- *Niclas Mrotzek (Germany)*

Activities and publications during the period 2015-2017

Introduction

The principal goal of the Joint Study Group 0.27 is to investigate the impact 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 etc.

Achieved results

Firstly, all members of the Joint Study Group have designed and completed a **work programme**. For this purpose we have collected and discussed different ideas. Each member has presented his expertise and resources, which can be used for the cooperation. Eventually, we have defined distinctive milestones. Furthermore, the program describes in detail different steps; the relations between the single work packages; a responsible person for the particular milestones and a time schedule.

We started to put the program into practice by installing 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. This website is available under www.igg.uni-bonn.de/apmg.

Two members of the Joint Study Group have worked on the **characterization of a superstorm**. At a first glance, this seems to be an easy matter, but it is far from being trivial, since we have to consider very complex relationships. Therefore a thorough analysis of previous solar events is necessary to extract regularities and to transfer a Carrington-event in our present time. Meanwhile, we accomplished a “preliminary data set” simulating a severe solar storm. The data set contains Kp- and ap-values as well as F10.7-indices. The data is delivered in standard formats, which is WDC for the Kp- and ap-values and which is FLUXTABLE.TXT for F10.7. Work on this issue is still going on in order to find parameters that characterize a today’s Carrington-event in the best way.

Based on this fundamental step, another group has started to work on producing **ionosphere states** for the period of this solar storm. Basically, it’s possible to take the above mentioned parameters as input for ionosphere models and then to compute the ionosphere for specific dates. The problem is that the models often are not designed for extreme events, and therefore quite a lot of adaption is required to use the simulated data as input. A different approach uses the Principal Component Analysis (PCA) by inverting the method, whereby the principal component of the dominant mode is substituted by e.g. a time series of a Carrington-event describing F10.7-index. The work on this subject is still in progress.

According to the work programme, the Joint Study Group investigates the effects of a solar superstorm. In detail, this means to examine the impact of a solar event on satellite motion (1); the impact of a solar event on GNSS (especially navigation) (2); the impact of a solar event on signal propagation w.r.t. communication-techniques (3); the impact of a solar event on re-entry computations(4); the impact of a solar event on the life-time of space debris (5) and the impact of a solar event on the International Space Station (6).

We partly started with the studies (1) to (6), and in particular for (1) we can present first results. Again, it is very important to point out that a Carrington-event is a very extreme storm. This means, we expect clear effects, but as the results show, the impact is drastic. Figure 23 shows the atmospheric drag for a LEO (height of 300 km) as a function of time.

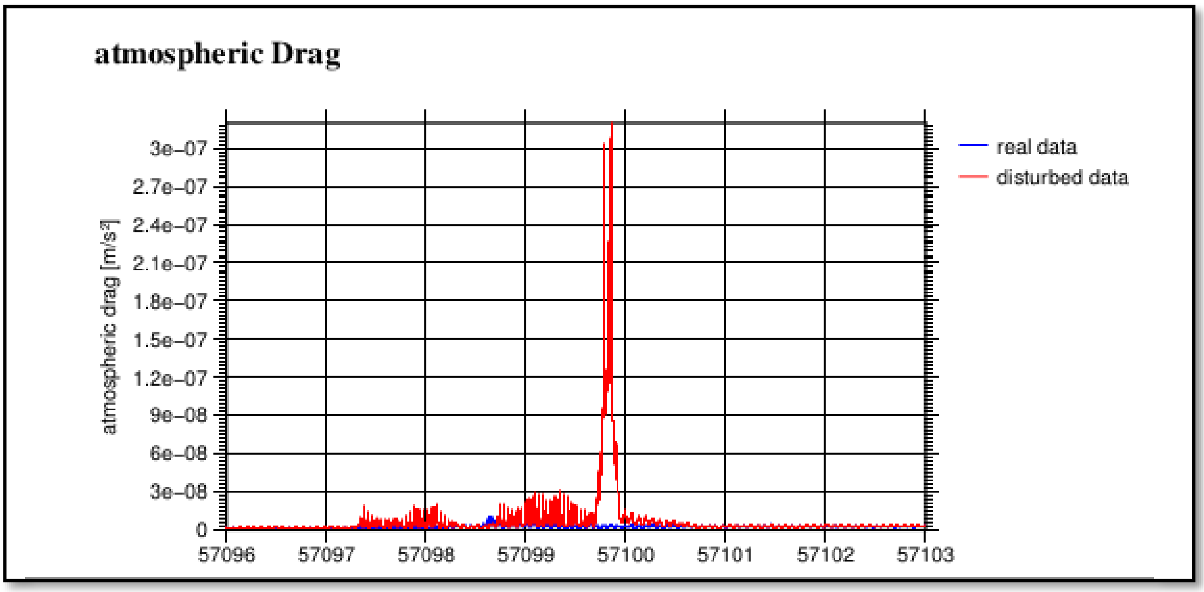

Figure 23: *Atmospheric drag for a test satellite*

The figure clearly shows, that the atmospheric drag enhances formidably. Consequently, the satellite experiences an enormous deceleration along track, when compared to an undisturbed satellite motion. Further computations show, that the satellite steadily gets lost and increasingly sinks.

These first results are very interesting and give a strong motivation for further and detailed analysis.

Further Activities

Members of the Joint Study Group visited conferences and workshops, in particular the "European Geosciences Union – General Assembly" in 2016 and 2017. Talks and posters were presented and some members had official positions like geodesy division president

(Michael Schmidt) or session conveners. Furthermore Michael Schmidt has established a "Focus Area on Geodetic Space Weather Research" within GGOS.

Outlook

The Joint Study Group has done important and valuable work. The initiated investigations have to be continued and the whole work has to be aligned strictly to the goals of the work programme. For the year 2018 a workshop is planned. Of course, final results have to be found and these results are supposed to be presented in a paper.

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

Chair: *Yoshiyuki Tanaka (Japan)*

Members

- *Shin-Chan Han (Australia)*
- *Guangyu Fu (China)*
- *Luce Fleitout (France)*
- *Johannes Bouman (Germany)*
- *Volker Klemann (Germany)*
- *Zdenêk Martinec (Ireland)*
- *Gabriele Cambiotti (Italy)*
- *Giorgio Spada (Italy)*
- *Masao Nakada (Japan)*
- *Jun'ichi Okuno (Japan)*
- *Yoshiyuki Tanaka (Japan)*
- *Taco Broerse (Netherlands)*
- *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)*

Activities and publications during the period 2015-2017

The research topics of the members, associated with time variations in deformation and gravity, cover a broad range. Here we report a brief summary of the selected results obtained by the members during 2015-2017. We set up a mailing list to share these results.

Earthquake and volcano problems

Han et al. (2016) revealed that the viscoelastic relaxation caused gravity change larger than the coseismic change for the 2006 Mw 8.3 thrust and 2007 Mw 8.1 normal fault earthquakes of the central Kuril Islands. Fuchs et al. (2016) obtained finely distributed fault slip model from GNSS and GRACE/GOCE satellite gravimetry for the coseismic and postseismic changes of the 2011 Tohoku-Oki earthquake. Broerse et al. (2015) analysed the GPS and GRACE data associated with the mantle relaxation due to the 2004 Sumatra-Andaman earthquake and found that the relaxation of the gravity field at GRACE resolution is much slower than what GPS observes over land in the back arc.

Crawford et al. (2017) developed a method that could be applied to both forward and inverse modelling of post-seismic deformation in a self-gravitating, heterogeneous and compressible

Earth with a variety of linear and nonlinear rheologies. Tanaka et al. (2015) developed a method to compute viscoelastic postseismic deformation in a compressible, self-gravitating spherical Earth with 3D viscosity distributions.

Crustal deformations induced by earthquakes were modelled for the 2014 South Napa earthquake (Polcari et al., 2016) and the Illapel 2015 Mw8.3earthquake (Klein et al., 2017). Shirzaei et al. (2016) constructed a poroelastic model and explained the surface uplift and time-dependent seismic hazard caused by fluid injection in eastern Texas. Deformations associated with volcanic activities were also modelled for Canary Islands (Fernández et al., 2015), Mount Etna (Cannavò et al., 2015), Fogo volcano (González et al., 2015a) and Campi Flegrei (Tiampo et al., 2017). Fullea et al. (2015) modelled 3D lithospheric-uppermost mantle thermochemical structure beneath the Canary Islands by integrating geophysical and petrological data plus GOCE data. González et al. (2015b) detected and modelled hydrothermal pressurization before the 2010 Eruption of Mount Sinabung Volcano with InSAR data. Volcano gravimetry and related theoretical developments were carried out by Pohánka et al. (2015), Vajda et al. (2015), Vajda (2016) and Zahorec et al. (2016).

González et al. (2015c) published a book dedicated to the description of theoretical models, inversion techniques and their application to observational geodetic and geophysical data sets, including deformation and gravity data, in active geodynamic areas and affected by natural hazards.

Plate tectonics

Regional deformation associated with plate motion was studied by Palano et al. (2015), where a large-scale clockwise rotation of the Iberian Peninsula with respect to stable Eurasia was found for the first time. This pattern is considered to partly reflect the quasi-continuous straining due to viscous coupling of the NW Nubia and Iberian plate boundary. Elliott et al. (2016) found that the Gorkha earthquake ruptured the Main Himalayan Thrust fault and revealed the seismotectonics in the Kathmandu area with geodetic data, combined with geologic, geomorphological and geophysical analyses.

Loading problems

Klemann et al. (2015) provided an overview of the rheological features of the lithosphere and of the upper mantle with respect to deformations of the solid Earth in response to time-varying surface loading of an SNRVEI model. Spada (2017) gave a review regarding the basic elements of the GIA theory, emphasizing the connections with current sea-level changes observed by tide gauges and altimetry. Pail et al. (2017) provided an assessment of the goals that future space gravity missions should strive for, and articulate quantitatively what the resolution, repeat observation time and mission lifetime that would be required to advocate for a rational Earth observing space mission. Ocean and atmospheric sciences, solid earth deformation, including earthquakes and land hydrology and cryospheric mass balance were all addressed. The launch date for such an advanced future gravity mission, with a possible series of satellites, is after the year 2025.

Martinec et al. (2015) developed a method for computing the sensitivity of the GIA forward solution with respect to the Earth's mantle viscosity and the gradient of data misfit with respect to viscosity parameters. These methods enabled an efficient inverse modelling of GIA-related observations by avoiding redundant parameter estimates. Caron et al. (2017) used a Bayesian Monte Carlo approach with a Markov chain formalism to invert the global GIA signal simultaneously for the mechanical properties of the mantle including Maxwell and Burgers rheologies and the volumes of the ice sheets. Greff-Lefftz et al. (2016) used global seismic velocities and geoid, gravity and gravity gradients to constrain the viscosity profile within the mantle as well as the lateral density variations, based on a Monte Carlo search. Riva et al. (2016) showed how land ice wastage through the last century had caused non-linear, location dependent vertical land motion with several tenths of mm/yr over large parts of the continents.

Regional GIA was modelled by Klemann et al. (2015) for Laptev Sea and the East Siberian Sea, Wolstencroft et al. (2015) for Palmer Land, Konrad et al. (2015) and van der Wal et al. (2015) for Antarctica, and van der Wal and IJpelaar (2017) for Fennoscandia. Richter et al. (2016) used a 43 geodetic GNSS stations with sufficiently long time series to reconstruct the viscoelastic vertical deformation field associated with mantle/lithosphere uplift following the retreat of the Southern Patagonian Icefield from the times of the present day Little Ice Age into the present-day. Tanaka et al. (2015) modelled the glacial isostatic rebound in southeast Alaska and showed that neglect of compressibility could potentially underestimate the mantle viscosity by approximately 30%. Adhikari et al. (2017) used the horizontal deformation observed in continuous GPS data on bedrock to identify and quantify a wave of ice and water discharge in the Rink outlet glacier that occurs only during summers of nearly complete surface melting of southwestern Greenland.

Dill et al. (2015) investigated the influence of the elastic Earth properties on seasonal or shorter periodic surface deformations due to atmospheric surface pressure and terrestrial water storage variations, and showed that elastic response could become very sensitive to inhomogeneities in the crustal structure, when hydrological signals were localized. Adhikari et al. (2016a) derived a numerical global earth deformational model for use with short-term (elastic) responses with rotational feedback and sea-level responses that are gravitationally self-consistent. The key element that is new is that the traditional Love number-based calculations may be transformed and performed on a highly adaptable mesh system. Such a mesh can include model projections that run at high (2-km) resolution ice sheet models. This 2-km resolution is required for calculation of shear margin stress and strain-rates of fast-moving outlet glaciers whose interiors may be marine based. Han (2017) discovered and quantified seasonal mode of continental 3D deformation, induced by atmospheric and hydrological cycles.

Tides and Earth rotation

Chao and Ding (2016) theoretically estimated coseismic effects on global geodynamic quantities due to 43,304 major events that have occurred during 1976–2015. In particular, the polar motion excitations due to the few greatest earthquakes since 2004 have facilitated the abrupt turn of the pole path observed during these years. Lau et al. (2015) developed a generalized normal mode theory for the tidal response within the semi-diurnal and long-period tidal band, which involves a perturbation method that permits an efficient calculation of the impact of aspherical structure on the tidal response. Ding and Chao (2016) analysed global GPS and superconducting gravimeter observations to determine the lower-mantle anelasticity through the solution of the complex Love numbers at the Chandler wobble period. Cambiotti et al. (2016) investigated polar motion caused by not only coseismic deformation but also the seismic cycles at the global scale for the first time. Sun et al. (2016) developed a method to estimate C20 variations by combining the GRACE data with geophysical models including an ocean bottom pressure model and a glacial isostatic model (GIA). The result is available at http://www.citg.tudelft.nl/c20. Nakada et al. (2015) examined the geodetically derived rotational variations for the rate of change of degree-two harmonics of Earth's geopotential and true polar wander, combining a recent melting model of glaciers and the Greenland and Antarctic ice sheets. The GIA-induced J2 dot estimated from the observations was significantly different from the values adopted to infer the viscosity structure of the mantle in most previous studies. Adhikari and Ivins (2016b) used IERS data, global GRACE Release 05 fields, ancillary model and SLR-derived fields to determine that 3 geophysical components dominate the non-secular pole position at frequencies lower than that of the Chandler Wobble since 2002. The 3 components are Antarctic mass balance (at 400 km resolution), Greenland mass balance (400 km resolution), and total global water storage changes on land. Critical to the success of recovering the polar motion is to compute the rotational feedback, global Sea Level Equation, elastic field, gravity field and mass transport from land to ocean.

<u>Highlights of our activities (selected)</u>

Vajda et al. (2015) revealed the effect of the deformation-induced topo effect that consists of the Free Air Effect (FAE) and the Topographic Deformation Effect (TDE) which is the Newtonian attraction of the masses within the topographic surface deformation rind (volumetric domain between pre– and post–deformation topo surfaces). By numerical assessment they showed that the approximation of FAE based on the normal (theoretical) free air gradient (FAG) differed significantly from that based on the true (in situ) vertical gradient of gravity (VGG). They showed also that the TDE evaluated using high resolution high accuracy DEMs and numerical 3D Newtonian integration differed significantly from its approximation based on a Bouguer term. Work is in progress to analyze the DITE for various synthetic vertical displacement fields and to study other approximations of DITE.

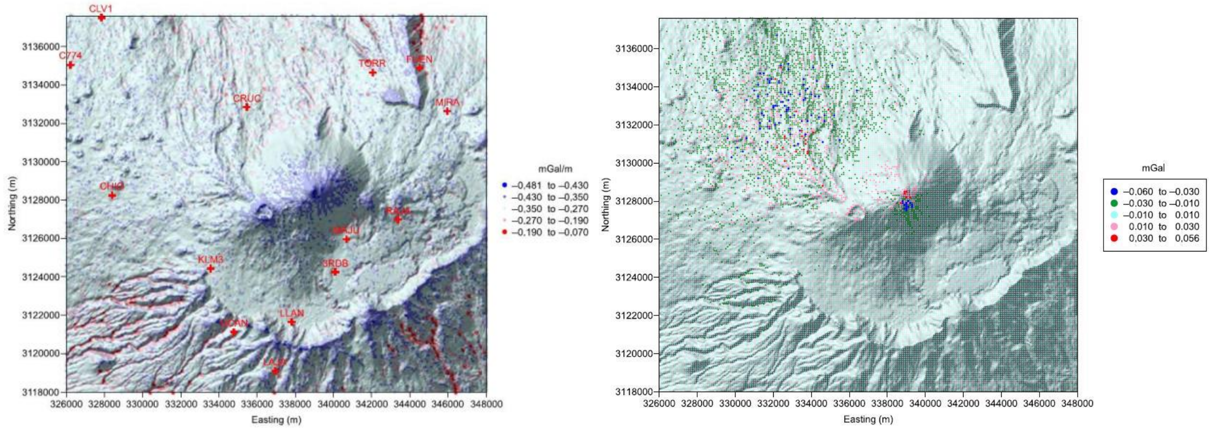

Figure 24: *Topographicaly predicted vertical gradient of gravity at CVC of Tenerife (left), differences between the TDE and its approximation by planar Bouguer effect at CVC of Tenerife (right)*

The benchmark study on solving the sea-level equation in GIA modelling is being supervised by Zdeněk Martinec (https://geofjv.troja.mff.cuni.cz/GIABenchmark/), where some of us are also participating in.

The sea-level load in GIA is described by the sea-level equation (SLE), which represents the mass redistribution between ice sheets and oceans on a deforming earth. Various levels of complexity of SLE have been proposed in the past. Despite various teams independently investigating GIA, there has been no systematic intercomparison amongst the solvers through which the methods may be validated. The goal of this activity is to present a series of benchmark experiments designed for testing and comparing numerical implementations of the SLE. The current benchmark uses an earth model for which Love numbers have been computed and benchmarked in Spada et al (2011). In spite of the significant differences in the numerical methods employed, the test computations performed so far show a satisfactory agreement between the results provided by the participants. The differences found can often be attributed to the different approximations inherent to the various algorithms.

Software development

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.

Meeting and workshop organization (selected)

Wouter van der Wal organizes IAG Workshop on Glacial Isostatic Adjustment and Elastic Deformation, held on September 5-7, 2017, at Grand Hotel Reykjavik, Iceland (URL:http://www.polar.dtu.dk/english/Workshop-on-Glacial-isostatic-adjustment-and-elastic-deformation-2017). Gabriele Cambiotti proposed and organized the session for the 2016 AGU fall meeting, "Interrelation between seismicity and gravity field anomalies - New insights into earthquake rupture processes". Jose Fernandez chaired the Session "Measuring changes at volcanoes using Geodesy: an update of methods and results" at AGU Fall Meeting, San Francisco, 14-18 December 2015".

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Joint Study Group 0.22: Definition and realization of global terrestrial reference frames

Chair: *Christopher Kotsakis (Greece)*

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- *Michael Bevis (USA)*
- *Mathis Bloßfeld (Germany)*
- *David Coulot (France)*
- *Athanasios Dermanis (Greece)*
- *Richard Gross (USA)*
- *Tom Herring (USA)*
- *Michael Schindelegger (Austria)*
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Activities and publications during the period 2015-2017

The report was not submitted.