The Inter-Commission Committee on Theory of the International Association of Geodesy

Final Report

Period covered: 2011–2015

May 2015

Inter-Commission on Theory (ICCT)

http://icct.kma.zcu.cz

President: Nico Sneeuw (Germany)
Vice President: Pavel Novák (Czech Republic)

Structure

Joint Study Group 0.1: Application of time series analysis in geodesy
Joint Study Group 0.2: Gravity field modelling in support of height system realization
Joint Study Group 0.3: Comparison of current methodologies in regional gravity field modelling
Joint Study Group 0.4: Coordinate systems in numerical weather models
Joint Study Group 0.5: Multi-sensor combination for the separation of integral geodetic signals
Joint Study Group 0.6: Applicability of current GRACE solution strategies to the next generation of inter-satellite range observations
Joint Study Group 0.7: Computational methods for high-resolution gravity field modelling and nonlinear diffusion filtering
Joint Study Group 0.8: Earth system interaction from space geodesy
Joint Study Group 0.9: Future developments of ITRF models and their geophysical interpretation

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.

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,
- to monitor research developments in geodetic modelling.

The structure of the ICCT is specified in the IAG by-laws. The ICCT Steering Committee consists of the President, the Vice-President and representatives from all IAG Commissions:

President: Nico Sneeuw (Germany)
Vice-President: Pavel Novák (Czech Republic)
Representatives:
Commission 1: Tonie van Dam (Luxembourg)
Commission 2: Urs Marti (Switzerland)
Commission 3: Richard Gross (USA)
Commission 4: Dorota Brzezinska (USA)
GGOS: Hans-Jörg Kutterer (Germany)

Website

Since 2007, the ICCT website is hosted at http://icct.kma.zcu.cz by the web server of the Department of Mathematics, 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. During 2008 the latest Study Group was established (IC-SG9), i.e., there are currently nine active Study Groups within the ICCT.

VIII Hotine-Marussi Symposium

The main highlight of ICCT is the organization of the VIII Hotine-Marussi Symposium in Rome. Since the inception of ICCT, the already existing series of Hotine-Marussi Symposia falls under the responsibility of ICCT. Earlier ICCT-organized Symposia were the numbers VI (2006, Wuhan) and VII (2009, Rome). June 17–21, 2013, the VIII Hotine-Marussi Symposium took place in Rome. The venue was the same as 2009, namely at the Faculty of Engineering of the Sapienza University of Rome. Also the local organization was in the hands of Prof. Mattia Crespi again. From a total attendance of about 100 participants about 70 oral presentations and 15 posters were contributed to the following sessions:

1. Geodetic Data Analysis (W. Kosek, R. Gross, C. Kreemer)
2. Theoretical aspects of reference frames (A. Dermanis, T. Van Dam)
3. Digital Terrain Modeling, Synthetic Aperture Radar and new sensors: theory and methods (M. Crespi, E. Pottier)
4. Geopotential modeling, boundary value problems and height systems (P. Novák, M. Schmidt, C. Gerlach)
5. Atmospheric modeling in geodesy (T. Hobiger, M. Schindelegger)
6. Gravity field mapping methodology from GRACE and future gravity missions (M. Weigelt, A. Jäggi)
7. Inverse modeling, estimation theory (P. Xu)
8. Computational geodesy (R. Čunderlík, K. Mikula)
9. Special Session at Accademia Nazionale dei Lincei (F. Sansò, R. Barzaghi, N. Sneeuw)

The session topics follow roughly the study group structure of ICCT. Conveners (in brackets) were recruited (mostly) from the study group chairs and members.

True to the InterCommission nature of ICCT, the sessions dealt with the full width of topics in theoretical geodesy. During the special session at the Accademia Nazionale dei Lincei Fernando Sansò was honoured for his long-term involvement in the organization of the series of Hotine-Marussi Symposium, after taking over the baton from Antonio Marussi in 1985. It was decided to rename the VIII Hotine-Marussi Symposium by adding "*in honour of Fernando Sansò*" to its title.

This report

The activities of the ICCT are related namely to the research carried out by members of its Joint Study Groups. Their final reports specify the areas investigated by the members of the Joint Study Groups, achieved results (publications and presentations). Based on the content of the reports, it can be concluded that the Joint Study Groups are active, although the level of mutual co-operation and/or interaction between its members is not necessarily the same for all the Joint Study Groups.

Joint Study Group 0.1: Application of Time Series Analysis in Geodesy

Chair: Wieslaw Kosek (Poland)

In October 2010 the US Naval Observatory (USNO 2013) together with the Space Research Centre (SRC 2013) in Warsaw initiated the IERS Earth Orientation Parameters Combination of Prediction Pilot Project (EOPCPPP). The goal of this project is to determine the feasibility of combining Earth Orientation Parameters (EOP) predictions on an operational basis. The pole coordinate data predictions from different prediction contributors and ensemble predictions computed by the USNO were studied to determine the statistical properties of polar motion forecasts (Kosek et al. 2012). Short term prediction errors of pole coordinates data are caused by wideband short period oscillations in joint atmospheric-ocean excitation functions and their increase can be also caused by the change of phase of the annual oscillation in this function (Kosek 2012). The combination of the least-squares and multivariate autoregressive prediction using the axial component of the atmospheric angular momentum excitation function method was applied to predict UT1–UTC data which improved their prediction accuracy in relation to the combination of the least-squares and the autoregressive prediction of the univariate time series (Niedzielski and Kosek 2012).

Higher order semblance function reveals that addition of hydrology angular momentum to the sum of atmospheric and oceanic excitation functions of polar motion improves the phase agreement between the geodetic and fluid excitation functions in the annual frequency band. The common oscillations in the geodetic and fluid excitation functions of polar motion can be detected using wavelet based semblance filtering (Kosek et al., 2011).

At the University of Wroclaw in Poland the real time system and service for sea level prediction called PROGNOCEAN has been built (Niedzielski and Mizinski 2013). The aim of this system is computation of alitmeter-derived sea level anomelies data prediction for 1 day, 1 week and 2 weeks in the future, together with the maps of the mean prediction errors. The predictions are computed in real time, so the users are available to evaluate the performance of the system and service. The forecasting strategies are based on a few time series methods: (1) extrapolation of the polynomial-harmonic model, (2) extrapolation of the polynomial-harmonic model with autoregressive prediction, (3) extrapolation of the polynomial-harmonic model with self-exciting threshold autoregressive model, (4) extrapolation of the polynomial-harmonic model with autocovariance prediction, (5) extrapolation of the polynomial-harmonic model with vector autoregressive prediction, (6) extrapolation of the polynomial-harmonic model with generalized space-time autoregressive model (Prognocean 2013).

A software package TSoft for the analysis of Time Series and Earth Tides has been created by by Paul Vauterin in the Royal Observatory of Belgium. It allows the user to process the data in a fully interactive and graphical way and has a number of important advantages, particularly in the field of error correction of (strongly perturbed) data, and the detection and processing of special events (e.g. free oscillations after Earthquakes (ROB 2013).

The influence of the hydrological noise on repeated gravity measurements has been investigated on the basis of the time series of 18 superconducting gravimeters (SGs) and on predictions inferred from the Land Dynamics (LaD) world Gascoyne land water energy balances model. It is shown that the PSDs of the hydrological effects flattens at low frequency and is characterized by a generalized Gauss Markov structure (Van Camp et al. 2010).

The new method of data processing was used for the absolute gravimeters (AGs) observations during intercomparison campaigns since 1980. A new criterion, based on the minimization of the L1 norm of the offsets, for fixing the constant of the ill-conditioned problem, was found to be statistically more precise than the one classically used (de Viron et al. 2011). Based on synthetic data representative of signals observed by superconducting gravimeters (SG) at various station locations, it was found that the addition of SG information mitigates the error in the estimation of gravity rates of change caused by the presence of long period, interannual, and annual signals in the AGs data. These results were discussed as a function of the sampling rate of the absolute gravity measurements, the duration of the observations, and the uncertainties of the AGs (Van Camp et al. 2013).

It was shown that 25 different climate indices associated with a great variety of climatic fields and geographic regions share a very substantial fraction of their variability. This common fraction can be captured and described by using no more than four leading modes of variability correlated with the sea surface temperature field. The preferred periodicities apparent in these modes reflect mainly the quasi-biennial and quasiquadrennial periodicities of El Nino Southern Oscillation (de Viron et al. 2013).

Meetings

Since 2011 at each European Geosciences Union General Assembly the sessions G1.2 "Mathematical methods in the analysis and interpretation of potential field data and other geodetic time series" were organized, by two members of the JSG 0.1 study group (EGU 2011, 2012, 2013).

Publications

Kosek W., Popiński W., Niedzielski T., 2011. Wavelet based comparison of high frequency oscillations in the geodetic and fluid excitation functions of polar motion. In: Proceedings of the “Journées 2008 Systèmes de référence spatio-temporels”, Capitaine N. (ed.), Observatoire de Paris, 168-171.

Kosek W., 2012, Future improvements in EOP prediction, Proc. IAG 2009, "Geodesy for Planet Earth", Aug. 31 - Sep. 4, 2009, Buenos Aires, Argentina. S. Kenyon, M. C. Pacino, and U. Marti (eds.), Geodesy for Planet Earth, International Association of Geodesy Symposia series 136, Springer-Verlag Berlin Heidelberg 2011, DOI 10.1007/978-3-642-20338-1_62, pp. 511-518.

Kosek W., B. Luzum, M. Kalarus, A. Wnęk and M. Zbylut, 2012, Analysis of Pole Coordinate Data Predictions in the Earth Orientation Parameters Combination of Prediction Pilot Project, Artificial Satellites, Vol. 46, No 4/2011, DOI 10.2478/v10018-012-0006-x, 139-150.

Niedzielski T., 2011. Is there any teleconnection between surface hydrology in Poland and El Niño/Southern Oscillation? Pure and Applied Geophysics 168, 871-886.

Niedzielski T., Kosek W., 2011. Nonlinear sea level variations in the equatorial Pacific due to ENSO. In: Proceedings of the “Journées 2008 Systèmes de référence spatio-temporels”, Capitaine N. (ed.), Observatoire de Paris, 217-218.

Niedzielski T., Kosek W., 2011. Minimum time span of TOPEX/Poseidon, Jason-1 and Jason-2 global altimeter data to detect a significant trend and acceleration in sea level change. Advances in Space Research 47, 1248-1255.

Niedzielski T., Kosek W., 2012. The statistical characteristics of altimetric sea level anomaly time series. In: Kenyon S., Pacino M.C., Marti U. (eds.), Geodesy for Planet Earth, International Association of Geodesy Symposia 136, Springer, 545-549.

Niedzielski T., Kosek, 2012, Prediction analysis of UT1–UTC time series by combination of the least-squares and multivariate autoregressive method, VII Hotine-Marussi Symposium on Mathematical Geodesy, Proceedings of the Symposium in Rome, 6-10 June, 2009 Series: International Association of Geodesy Symposia, Tentative volume 137, Sneeuw, N.; Novák, P.; Crespi, M.; Sansò, F. (Eds.), DOI 10.1007/978-3-642-22078-4, pp. 153-157.

Niedzielski T., Miziński B., 2013. Automated system for near-real time modelling and prediction of altimeter-derived sea level anomalies. Computers & Geosciences 58, 29-39.

Prognocean 2013, http://www.ocean.uni.wroc.pl/index.php/sea-level-prediction/27-near-real-time-service-for-sea-level-prediction

ROB 2013, http://www.seismologie.be/TSOFT/tsoft.html

SRC 2013, http://www.cbk.waw.pl/eopcppp/cfp.html

USNO 2013, http://maia.usno.navy.mil/eopcppp/

Van Camp, M., L. Métivier, O. de Viron, B. Meurers, and S. D. P. Williams, 2010, Characterizing long-time scale hydrological effects on gravity for improved distinction of tectonic signals. Journal of Geophysical Research, VOL. 115, B07407, doi:10.1029/2009JB006615, 2010

Van Camp M., O. de Viron, R.J. Warburton, Improving the determination of the gravity rate of change by combining superconducting with absolute gravimeter data, Computers & Geosciences 51 (2013) 49–55

de Viron O., M Van Camp, and O Francis, 2011, Revisiting absolute gravimeter intercomparisons, Metrologia 48 (2011) 290–298 doi:10.1088/0026-1394/48/5/008.

de Viron O., J. O. Dickey, and M. Ghil, 2013, Global modes of climate variability, Geophysical Research Letters, VOL. 40, 1–6, doi:10.1002/grl.50386, 2013

Joint Study Group 0.2: Gravity Field Modelling in Support of Height System Realization

Chair: Pavel Novák (Czech Republic)

1. Introduction and objectives

This report describes activities and scientific outputs of the ICCT's Joint Study Group 0.2 for the period of 2011-15. In its terms of reference, the group members investigated several research topics of a theoretical nature that were closely related to gravity field modelling at all scales in service of establishing a world height system (WHS). Namely geometric properties of the Earth's gravity field are very significant in this respect as one of its equipotential surfaces serves as a global vertical datum in geodesy.

Theoretical issues investigated by JSG0.2 have included the following topics:

- Combining heterogeneous gravity field observables by using spatial inversion, spherical radial functions, collocation and wavelets, etc. and by taking into account their sampling in time and space, spectral and stochastic properties.
- Studying stable, accurate and numerically efficient methods for continuation of gravity field parameters including satellite observables of type GRACE and GOCE.
- Advancing methods for gravity potential estimation based on its measured directional derivatives (gravity and gravity gradients) by exploiting advantages of simultaneous continuation and inversion of observations.
- Investigating gravity data specifications (stochastic properties, spatial and temporal sampling and spectral content) required by specific geodetic applications.
- Studying available Earth's gravitational models (EGM) in terms of their available resolution and accuracy for the purpose of WHS realization.
- Defining relations between an adopted conventional EGM and parameters of a geocentric reference ellipsoid of revolution approximating a time invariant equipotential surface of the adopted EGM aligned to reduced observables of mean sea level.

This study group (SG) is affiliated to IAG Commissions 1 (*Reference Frames*) and 2 (*Gravity Field*); co-operation with the GGOS Theme 1 *Unified Global Height System* was undertaken.

2. Report on published/presented results of the study group

Main scientific outcomes of JSG0.2 include journal publications, oral and poster presentations at international conferences and meetings, as well as progress and final reports delivered to various scientific authorities. Major meetings organized within 2011-15 (such as GGHS 2012, IAG Scientific Meeting 2013, Hotine-Marussi 2013, ESA Living Planet 2013, IGFS 2014, IUGG 2015 as well as annual meetings of EGU, CGU and AGU) included sessions on global geopotential models, vertical datum unification and local gravity field modelling. The following overview provides merely selected publications and presentations.

2.1. Selected publications

Čunderlík R, Mikula K, Špir R (2012) An oblique derivative in the direct BEM formulation of the fixed gravimetric BVP. In: *7th Hotine-Marussi Symposium on Mathematical Geodesy*. International Association of Geodesy Symposia 137, DOI: 10.1007/978-3-642-22078-4_34.

Čunderlík R, Fašková Z, Mikula K (2012) Fixed gravimetric BVP for the vertical datum problem. In: *Geodesy for Planet Earth. International Association of Geodesy Symposia* 136, DOI: 10.1007/978-3-642-20338-1_40.

Čunderlík R, Minarechová Z, Mikula K (2014) Realization of WHS based on the static gravity field observed by GOCE. *International Association of Geodesy Symposia* 141: 211-220.

Featherstone WE (2013) Deterministic, stochastic, hybrid and band-limited modifications of Hotine's integral. *Journal of Geodesy* 87(5): 487-500, DOI: 10.1007/s00190-013-0612-9.

Filmer MS, Hirt C, Featherstone WE (2013) Error sources and data limitations for the prediction of surface gravity: a case study using benchmarks. *Studia Geophysica et Geodaetica* 57(1): 47-66, DOI: 10.1007/s11200-012-1114-6.

Featherstone WE, Filmer MS (2012) The north-south tilt in the Australian Height Datum is explained by the ocean's mean dynamic topography. *Journal of Geophysical Research – Oceans* 117: C08035, DOI: 10.1029/2012JC007974.

Hirt C, Kuhn M, Featherstone WE (2012) Topographic/isostatic evaluation of new-generation GOCE gravity field models. *Journal of Geophysical Research – Solid Earth* 117: B05407, DOI: 10.1029/2011JB008878.

Heck B (2011) A Brovar-type solution of the fixed geodetic boundary-value problem. *Studia Geophysica et Geodaetica* 55(3): 441-454, DOI: 10.1007/s11200-011-0025-2.

Gerlach C, Rummel R (2014) Global height system unification with GOCE: a simulation study on the indirect bias term in the GBVP approach. *Journal of Geodesy* 87(1): 57-67.

Gruber C, Novák P, Sebera J (2011) FFT-based high-performance spherical harmonic transformation. *Studia Geophysica et Geodaetica* 55(3): 489-500.

Gruber T, Gerlach C, Haagmans R (2013) Intercontinental height datum connection with GOCE and GPS-levelling data. *Journal of Geodetic Science* 2(4): 270–280.

Kotsakis C (2013) A conventional approach for comparing vertical reference frames. *Journal of Geodetic Science* 2(4): 319-324.

Novák P, Tenzer R (2013) Gravitational gradients at satellite altitudes in global geophysical studies. *Surveys in Geophysics* 34(5): 653-673.

Rummel R (2013) Height unification using GOCE. *Journal of Geodetic Science* 2(4): 355-362.

Rummel R, Gruber T, Ihde J, Liebsch G, Rülke A, Schäfer U, Sideris MG, Rangelova E, Woodworth P, Hughes C (2014) Height system unification with GOCE. Final report of the ESA project STSE – GOCE+, GO-HSU-RP-0021.

Sjoeberg LE, Eshagh M (2012) A theory on geoid modelling by spectral combination of data from satellite gravity gradiometry, terrestrial gravity and an Earth gravitational model. *Studia Geophysica et Geodaetica* 47(1): 13-28, DOI: 10.1556/AGeod.47.2012.1.2.

Sjoeberg LE (2011) Geoid determination by spectral combination of an Earth gravitational model with airborne and terrestrial gravimetry – a theoretical study. *Studia Geophysica et Geodaetica* 5(4): 579-588, DOI: 10.1007/s11200-010-0069-8.

Sideris MG, Rangelova E, Amjadiparvar B (2014) First results on height system unification in North America using GOCE. *International Association of Geodesy Symposia* 141: 221-227.

Sebera J, Šprlák, Novák P, Bezděk A, Val'ko M (2014) Iterative spherical downward continuation applied to magnetic and gravitational satellite data. *Surveys in Geophysics* 35(4): 941-958.

Sebera J, Pitoňák M, Hamáčková E, Novák P (2015). Comparative study of the spherical downward continuation. *Surveys in Geophysics* 36(2): 253-267.

Šprlák M, Sebera J, Val'ko M, Novák P (2014) Spherical integral formulas for upward & downward continuation of gravitational gradients onto gravitational gradients. *Journal of Geodesy* 88(2): 179–197.

Šprlák M, Novák P (2014) Integral transformations of gradiometric data onto GRACE type of observable. *Journal of Geodesy* 88(4): 377-390.

Šprlák M, Novák P (2014) Integral transformations of deflections of the vertical onto satellite-to-satellite tracking and gradiometric data. *Journal of Geodesy* 88(7): 643-657.

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.

Tenzer R, Hamayan, Novák P, Gladkikh V, Vajda P (2012) Global crust-mantle density contrast estimated from EGM2008, DTM2008, CRUST2.0 and ICE-5G. *Pure and Applied Geophysics* 169(9): 1663-1678.

Tenzer R, Novák P, Gladkikh V (2012) The bathymetric stripping corrections to gravity field quantities for a depth-dependent model of seawater density. *Marine Geodesy* 35: 1-23.

Tenzer R, Novák P (2013) Effect of crustal density structures on GOCE gravity gradient observables. *Terrestrial, Atmospheric and Oceanic Sciences* 24(5): 793-807.

Tenzer R, Chen W, Tsoulis D, Bagherbandi M, Sjoeberg LE, Novák P, Jin S (2015). Analysis of the refined CRUST1.0 crustal model and its gravity field. *Surveys in Geophysics* 36(1): 139-165.

Woodworth PL, Hughes CW, Bingham RJ, Gruber T (2013) Towards worldwide height system unification using ocean information. *Journal of Geodetic Science* 2(4): 302–318.

2.2. Selected oral and poster presentations

Abd-Elmotaal H, Kuehtreiber N (2012) Comparison between astro-gravimetric and astro-geodetic geoids for Austria. EGU2012-223.

Amjadiparvar B, Rangelova E, Sideris MG, Hayden TS (2013) The role of local gravity information in the unification of the North American vertical datums. EGU2013-6480.

Čunderlík R, Mikula K (2012) Realization of WHS based on the static gravity field observed by GOCE. International Symposium on Gravity, Geoid and Height Systems (GGHS2012). Venice, October 2012 (S5-179).

Elhabiby MM, Sideris MG, Keller W (2011) A combined multi-resolution multi-dimensional wavelet approach for the inversion of geodetic integrals. EGU2011-13775.

Fašková Z, Macák M, Čunderlík R, Mikula K (2012) Finite volume numerical scheme for high-resolution gravity field modelling and its parallel implementation. EGU2012-8827.

Gruber C, Novák P, Barthelmes F (2011) Derivation of topographic potential from global DEM models. EGU2011-10170.

Gruber C, Moon YJ, Flechtner F, Novák P, Daras I (2011) Submonthly GRACE solutions from localising integral equations and Kalman filtering. 25th General Assembly of IUGG, Melbourne, July 2011.

Gruber T, Rummel R, Sideris MG, Rangelova E, Woodworth P, Hughes C, Ihde J, Liebsch G, Schäfer U, Rülke A, Gerlach C, Haagmans R (2013) Height system unification with GOCE: overview and selected results. ESA Living Planet Symposium, Edinburgh, September 2013.

Gruber T, Rummel R, Sideris MG, Rangelova E, Woodworth P, Hughes C, Ihde J, Liebsch G, Schäfer U, Rülke A, Gerlach C, Haagmans R (2014) Scientific Roadmap towards Height System Unification with GOCE. 3rd International Gravity Field Service Meeting, Shanghai, July 2014.

Heck B, Müßle M, Seitz K, Grombein T (2013) On the effect of planar approximation in the geodetic boundary value problem. EGU2013-8963.

Huang J, Véronneau M (2013) Contribution of the GRACE and GOCE models to a geopotential-based geodetic vertical datum in Canada. EGU2013-10164.

Novák P, Sebera J, Val'ko M (2012) On the downward continuation of gravitational gradients. International Symposium on Gravity, Geoid and Height Systems (GGHS2012). Venice, October 2012 (S2-201).

Roman D, Véronneau M, Avalos D, Li X, Holmes S, Huang J (2012) Integration of gravity data into a seamless transnational height model for North America. International Symposium on Gravity, Geoid and Height Systems (GGHS2012). Venice, October 2012 (S5-075).

Rummel R, Gruber T, Gerlach C, Hughes C, Ihde J, Liebsch G, Rangelova E, Sideris MG, Woodworth P (2011) GOCE's impact on World Height System unification. AGU Fall Meeting, San Francisco, December 2011.

Sideris MG, Rangelova E (2012) First results on height systems unification in North America using GOCE. International Symposium on Gravity, Geoid and Height Systems (GGHS2012). Venice, October 2012 (S5-092).

Sideris MG, Rangelova E (2012) Global Height System Unification by means of the GOCE geoid. International Jubilee Conference UACEG2012, Calgary, November 2012.

Sebera J, Novák P, Vaľko M, Šprlák M, Bezděk A, Bouman J, Fuchs M (2013) Downward continuation of gridded and reprocessed GOCE gravitational gradients. EGU2013-8265.

Sebera J, Novák P, Val'ko M, Šprlák M, Bouman J, Fuchs M, Haagmans R (2014) Grids of GOCE-only gravitational gradients for geophysical applications. 11th EGU General Assembly, Vienna, April-May 2014.

Šprlák M, Novák P, Val'ko M, Sebera J (2013) Spherical integral formulas for upward/downward continuation of gravitational gradients onto gravitational gradients. 8th Hotine-Marussi Symposium, Rome, June 2013.

Šprlák M, Novák P, Val'ko M, Sebera J (2013) Comparison of three methods for the downward continuation of the gravitational gradients. ESA Living Planet Symposium, Edinburgh, September 2013.

Šprlák M, Novák P, Hamáčková E, Sebera J (2014) Integral transformations of disturbing potential onto gradiometric data. 11th EGU General Assembly, Vienna, April-May 2014.

Šprlák M, Hamáčková E, Novák P (2014) Validation of GOCE gravitational gradients by satellite altimetry. AGU Fall Meeting, San Francisco, December 2014.

Vergos GS, Andritsanos VD, Grigoriadis VN, Pagounis V, Tziavos IN (2014) Evaluation of GOCE/GRACE GGMs over Attika and Thessaloniki, Greece, and W0 determination for height system unification. 3rd International Gravity Field Service Meeting, Shanghai, July 2014.

Wang YM, Li X, Holmes S, Roman D, Smith D (2013) Investigation of the use of deflections of vertical measured by DIADEM camera in the GSVS11 survey. EGU2013-12779.

2.3. Study group web page

The webpage of the Joint Study Group 0.2 was http://icct.kma.zcu.cz/index.php/IC_SG2.

3. Report on activities of the study group

During the 2011-15 period, there were no specific sessions organized during regular geodetic conferences but one at the Hotine-Marussi Symposium 2013 in Rome. At this symposium organized by ICCT a session on geopotential modelling, boundary-value problems and height systems co-convened by the chairmen of JSG0.2 and JSG0.3 has been organized with total 11 oral and 2 poster presentations. However, other contributions of the JSG0.2's members can be found in programs of many geodetic and geophysical conferences and meetings (such as ESA's Living Planet 2013, annual meetings of AGU, CGU and EGU, GGHS 2012, IAG SM 2013, IGFS 2014 or IUGG 2015) organized within the period starting after the IUGG General Assembly in Melbourne and ending by the IUGG Assembly in Prague. Activities within the scope of the JSG partially overlapped with R&D project activities of its members including two projects funded through the ESA's Support to Science Element (STSE) program (GOCE data in support of WHS realization and GOCE data for geophysical exploration). These international projects represented a major platform for international scientific co-operation of scientists – members of JSG – including their regular meetings and mutual visits.

4. Outlook and plans

As IAG's efforts to establish a unified world height system are still ongoing, there will be further requirements for advancing theoretical foundations and investigations in the area of defining and establishing a global vertical datum that could be used for merging and unifying local and regional height systems and vertical datums used by different countries. Activities advanced within the 2011-15 period by this JSG shall continue in the 4 year period starting after the IUGG General Assembly 2015 with more stress on closer cooperation with IAG's commissions and namely with GGOS. Due to strong links and some overlaps with JSG0.3 their activities could possibly be merged under the umbrella of one JSG for the period of 2015-19 reflecting demands and requirements reflecting recent work progress on the WHS realization.

Joint Study Group 0.3: Comparison of Current Methodologies in Regional Gravity Field Modelling

Chairs: Michael Schmidt, Christian Gerlach (Germany)

Introduction

The main objectives of JSG0.3 are:

- to collect information of available methodologies and strategies for regional modelling,
- to analyze the collected information in order to find specific properties of the different approaches and to find, why certain strategies have been chosen,
- to create a benchmark data set for comparative numerical studies,
- to carry out numerical comparisons between different solution strategies for estimating the model parameters and to validate the results with other approaches (spherical harmonic models, least-squares collocation, etc.),
- to quantify and interpret the differences of the comparisons with a focus on detection, explanation and treatment of inconsistencies and possible instabilities of the different approaches,
- to create guidelines for generating regional gravity solutions,
- to outline standards and conventions for future regional gravity products.

Since the focus is on the methodological foundations it is straightforward to compare different methodologies in regional gravity field modelling based on synthetic data.

A first initiative to motivate active contribution to this study was a workshop on regional potential field modelling (see next section). On the workshop it was agreed to prepare a set of simulated gravity field data which should be used for computing regional gravity field models by different groups employing different methodologies. This should facilitate a numerical comparison of the different approaches.

Workshop

On February 23-24, 2012, an international "Workshop on Regional Gravity and Geomagnetic Field Modelling" was held at the Bavarian Academy of Sciences and Humanities (BAdW) in Munich, Germany. The workshop was jointly organized by the German Geodetic Research Institute (DGFI, Michael Schmidt), the Commission for Geodesy and Glaciology of BAdW (KEG, Christian Gerlach) and the Institute for Geodesy and Geoinformatics of the University of Bonn (IGG, Jürgen Kusche).

The active participants were asked to present their modelling approach with regard to their

- field of application (gravity field, geomagnetic field, static or time-variable, etc.),
- the type of input data used (terrestrial, airborne, satellite data or a combination of those),
- the type of modelling approach used including choice of base functions and point grids, properties of the mathematical and stochastic models and details on the mathematical solution and regularization techniques which are employed.

- In addition, open question and specific problem areas were presented.

After a general introduction by Michael Schmidt on general aspects of regional modelling and the scope of the workshop several modelling approaches were presented by several groups. Table 1 gives an overview of the modelling approaches presented during the two workshop days. Altogether there were 31 participants from 11 different countries. The participation was not limited to the original members of JSG 0.3 which reflects the study groups open policy that interested research groups can join at any time.

Simulation Data

On the workshop it was agreed within the final discussion to generate a simulation data set to be used by all different groups in order to facilitate numerical comparison between the different methodologies. The data set was jointly prepared by DGFI and IGG Bonn; it is available from the web site of JGS 0.3 at http://jsg03.dgfi.badw.de. The data set is publicly available and all groups interested in testing their approach are invited to use the data set and share the results. First results of individual groups were presented during the VIII Hotine-Marussi Symposium in Rome, June 17-21, 2013. Comprehensive comparisons and evaluations of the individual results are planned for the beginning of 2014 and will be presented at the EGU General Assembly 2014 in Vienna at the end of April, so far results from the actively contributing groups are made available to JGS 0.3 by the end of 2013.

The data sets comprise terrestrial data on regular geographic coordinate grids, airborne data on synthetic flight tracks and satellite data along real orbits of GRACE and GOCE. They are provided for two test areas, namely in Europe and South America, both having an extension of 20° × 30°. The data is provided error-free along with time series of white noise errors.

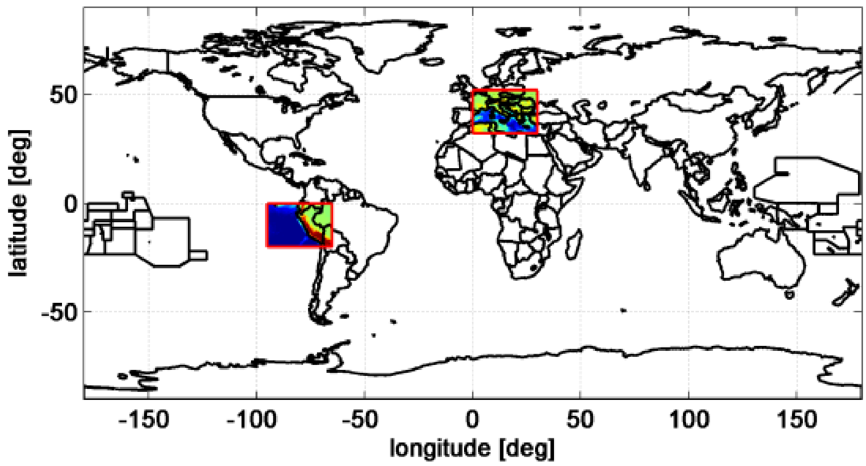

Figure 1: Global map with red boxes marking the test regions.

For validation of the computations from the data sets an additional data also on regular geographic surface grids is provided. In order to allow validation of gravity field approximation at independent locations, the validation grids are shifted with respect to the observation data grids.

Table 1: Overview of modelling approaches presented at the "Workshop on Regional Gravity and Geomagnetic Field Modelling"

Functional model (base function)	Field of Application	Research Group
Spherical splines	*Static and time-variable gravity field from satellite data*	*IGG, Bonn (Eicker, Schall, Kusche)*
Spherical radial basis functions	*Time-variable gravity field from satellite data*	*University of Life Sciences Ås, Norway (Bentel, Gerlach)*
Spherical radial basis functions	*Multi resolution representation of static and time-variable gravity field and combination of all data types*	*DGFI, Munich (Lieb, Schmidt)*
Poisson multipole wavelets	*Regional static gravity field refinement by combination of satellite and terrestrial data*	*IGN / IPGP Paris (Panet)*
Spherical radial basis functions	*Regional static and time-variable gravity field from satellite data*	*University Hannover (Naemi)*
Spherical radial basis functions	*Regional gravity field modelling from satellite data*	*University Stuttgart (Antoni)*
Slepian functions	*Spatiospectral locatlization on the sphere*	*Princeton University (Harig, Simons)*
Global directional wavelets	*Sensitivity of satellite formations and geomagnetic data analysis*	*Danish National Space Institute (Einarsson)*
Regional empirical orthonormal functions	*Geomagnetic field modeling*	*GFZ Potsdam (Schachtschneider)*
Poisson multipole wavelets	*Time variable gravity field from satellite data*	*University Potsdam (Fuhrmann)*
Harmonic splines	*Regional geomagnetic field*	*GFZ Potsdam (Lesur)*
Least-squares collocation	*Regional static gravity field from combination of all various data sources*	*Technical University Munich (Pail)*
Greens function	*Regional time-variable gravity field from satellite data*	*GFZ Potsdam (Fagioligni, Gruber)*
Isoparametric boundary elements	*Regional gravity field from satellite data*	*University Stuttgart (Weigelt)*
Point mass modelling	*Regional gravity field and geoid models from all available data*	*BKG Frankfurt (Schäfer)*

Comparisons of regional models

At the EGU General Assembly 2014 several group members presented their regional gravity field approaches within the Session G1.2: "Mathematical methods for the analysis of potential field data and geodetic time series", which was partly dedicated to the topics of the JSG 0.3. To be more specific, the regional approaches were applied either to single data sets such as GOCE gravity gradients or terrestrial data, but also to the combination of different observation types. Because the full gravity signal can only be derived from global sets of observational data, all of the regional solutions were derived in the classical remove-compute-restore procedure. Thereby, a global gravity field model is used to reduce the long wavelength part from the observations. After regional modeling of the residual field in the investigation area, the long wavelength part is restored again. The global background model and its resolution differ for the various simulation scenarios.

The following approaches have been employed in detail in these studies:

1. Spherical scaling functions on a Reuter grid (employing the Shannon function in the analysis step and the Blackman function for the synthesis step); solution by variance component estimation (VCE); *(DGFI, Munich: Lieb, Schmidt)*
2. Spherical wavelets on a Reuter grid (employing the cubic polynomial scaling function for analysis and synthesis); solution by VCE *(University of Life Sciences Ås, Norway; Jet Propulsion Laboratory, Pasadena: Bentel, Gerlach)*
3. Spherical spline functions on a triangular grid (employing Kaula's degree variance model as shaping function); solution by VCE, *(IGG, Bonn: Eicker, Schall, Kusche)*
4. Reduced point masses (basis functions are disturbing potential values obtained from point masses located on a regular grid on the Bjerhammer sphere with a $0.25° \times 0.5°$ spacing and a depth of 20 km), (*University of Copenhagen, Denmark: Tscherning, Herceg),*
5. Least-squares collocation (all admissible data are used), (*University of Copenhagen, Denmark: Tscherning, Herceg).*

Besides the solutions of these methods, calculations stemming from other regional modeling approaches such as expansions in Slepian basis functions have been presented. All the results have been rated as extremely valuable for reaching the goals of the Study Group.

To put the obtained numerical results of the regional solutions in perspective to what is expected from global spherical harmonic (SH) modelling a global data set of GOCE gravity gradients T_{rr} along the real GOCE orbits was generated from EGM2008 up to degree and order 250. As in case of the simulated regional data sets the gravity gradients are provided error-free along with a time series of white noise errors. Equivalently to the regional data sets also a global validation data set was performed.

Comparisons of regional models with a global spherical harmonic solution

At the EGU General Assembly 2015, again in the Session G1.2: "Mathematical methods for the analysis of potential field data and geodetic time series", several closed-loop scenarios were presented related to the comparison of the global SH solution - calculated from the global simulated GOCE gravity gradient T_{rr} data mentioned before - with corresponding regional solutions following the strategies (1) and (3) of the aforementioned list. The comparisons with the validation data from EGM2008 for the two test areas in Europe and in South America demonstrated that all solutions are of similar accuracy. Thus, it was concluded that the two RBF approaches using only regional input data, are at least of the same quality as global spherical harmonic models. However, it has to be pointed out that the chosen input data generated from EGM2008 cannot be used to show that a regional approach could be even "better" than the global approach. For such an investigation input data has to be chosen which is not stemming from a spherical harmonic model.

Other mentionable remarks

As an additional outcome of the investigations of the Study Group the two doctoral theses of Majid Naeimi: "Inversion of satellite gravity data using spherical radial base functions" and Katrin Bentel: "Regional Gravity Modeling in Spherical Radial Basis Functions - On the Role of the Basis Function and the Combination of Different Observation Types" have been completed successfully at the Institute of Geodesy of the Leibniz University Hannover at

August 23, 2013 and at the Department of Mathematical Sciences and Technology of the University of Life Sciences Ås in Norway at November 13, 2013, respectively. Some other Study Group members are currently working on their PhD thesis also directly related to the topics of and the studies within the JSG 0.3.

At the 24th of October 2014 our Study Group member Carl Christian Tscherning passed away unexpectedly. We want to express our deep sorrow about the loss of one of the most famous geodesists of the last decades. We miss him and with him the discussions about the pros and cons of different regional gravity field strategies.

Final remarks

Finally, we can state that from the range of results after many years of research and the four years lifetime of the JSG 0.3 a lot of information and progress was gained from systematic tuning of regional methods in combination with simulated gravity field data. Since all the work done in the last years within the JSG 0.3 is related to static regional gravity field modelling, a logical extension for the next 4 year period is the integration of the time dependency. Since regional approaches are in particular important for studying time evolving processes such as hydrology variations, the inclusion of a time-dependent model part is indispensable. Other issues, such as the multi-scale-analysis or the combination of point observations with area measurements are still unsolved.

Joint Study Group 0.4: Coordinate Systems in Numerical Weather Models

Chair: Thomas Hobiger (Sweden)

Numerical weather models (NWM's) contain valuable information relevant for removing the environmental signal from geodetic data. Currently no clear documentation exists regarding how to deal with the height systems when carrying out the calculations in a geodetic reference frame. A "conventional" transformation model (available also as source code) would enable geodesists to handle such data easily and allow them to use data from different meteorologic datasets. In addition, geodetic products such as GNSS-derived zenith total delays are being assimilated into NWMs. Thus, the transformations that convert the meteorological data into a geodetic reference frame should also support the use of geodetic data in meteorological models. This study group was set up to 1) deal with the differences between geodetic and meteorologic reference systems and 2) provide consistent models for transforming between the two systems.

Vertical transformation

In order to decide on a consistent transformation to/from numerical weather models the study group investigated vertical transformation first, before making a decision on how to deal with horizontal coordinates.

Ellipsoidal heights ↔ geopotential heights

Ellipsoidal heights (h) can be obtained from orthometric heights (H) when the geoid height (N) is known.

$$h = H + N \tag{1}$$

Furthermore, orthometric heights relate to geopotential heights (Z) by

$$H = Z \ g_n / g_0 \tag{2}$$

where g_n denotes the conventional gravity constant used throughout the numerical weather model. g_0 is the mean gravity, defined as

$$g_0 = 1/\zeta \int g \, dz \tag{3}$$

where the (vertical) integration is performed from the geoid surface to height ζ.

Error sources

Although the transformation between numerical weather model heights and geodetic (ellipsoidal) heights can be described in a mathematically unique sense (equations 1-3) the choice of geophysical models, the selection of constants, or the definition of the origin can lead to uncertainties of the transformation which can reach several meters. Thus, in the next sections the following effects on ellipsoidal heights are studied:

- Impact of the gravity model and the way in which the mean gravity (g_0) is calculated
- Impact of using the vertical direction w.r.t. the ellipsoid instead of the vertical w.r.t. a sphere (as used for numerical weather models)
- Uncertainty of the geoid (height)
- Using a different value for the gravity constant.

In order to choose the mean gravity for the height transformation the study group has investigated how and to what extent the choice of the gravity model changes the obtained ellipsoidal height. In doing so, geopotential heights from a numerical weather model (g_n=9.80665 m/s^2) [Taylor and Thompson] had to be transformed to ellipsoidal heights (assuming a constant geoid height of N=20 m). Calculations were performed on global 1°x1° grids, and it was assumed that geodetic latitude/longitude is identical to the one used in the

numerical weather models. In total eight contributions (from GFZ/Germany, GRGS/France, NICT/Japan, UNB/Canada(5 solutions) and TU Wien/Austria) were submitted. Fitting a linear function over all results allows the derivation of a simple estimate for the uncertainty due to the choice of the mean gravity (see figure 0.4).
When the normal to the sphere is used instead of the normal to the ellipsoid, transformed heights are expected to change slightly as well. In a similar study about the mean gravity model, GRGS evaluated data at various heights and grid points and computed the difference between two transformations, one using the normal to the ellipsoid and one using the normal w.r.t. a mean sphere.
Geoid heights N must be obtained from regional or global geoid models and applied to all grid points of the numerical weather model before obtaining ellipsoidal heights from orthometric heights (Equation 1). Thus, any error in these models directly propagates into the calculated ellipsoidal heights. Although regional geoid solutions can provide mm-accuracy, such models do not cover the whole area of the numerical weather model. Thus, an error of 1 cm is taken as a (conservative) value for the uncertainty of geoid heights on a global scale.
In case the gravity constant is inaccurate and not properly considered for the transformation, an additional error source for obtaining ellipsoidal heights results. However, most of the NWMs rely on a value of g_n=9.80665 m/s^2 or explicitly document the usage of another value. Thus, the impact from this error source can be assumed to be zero.

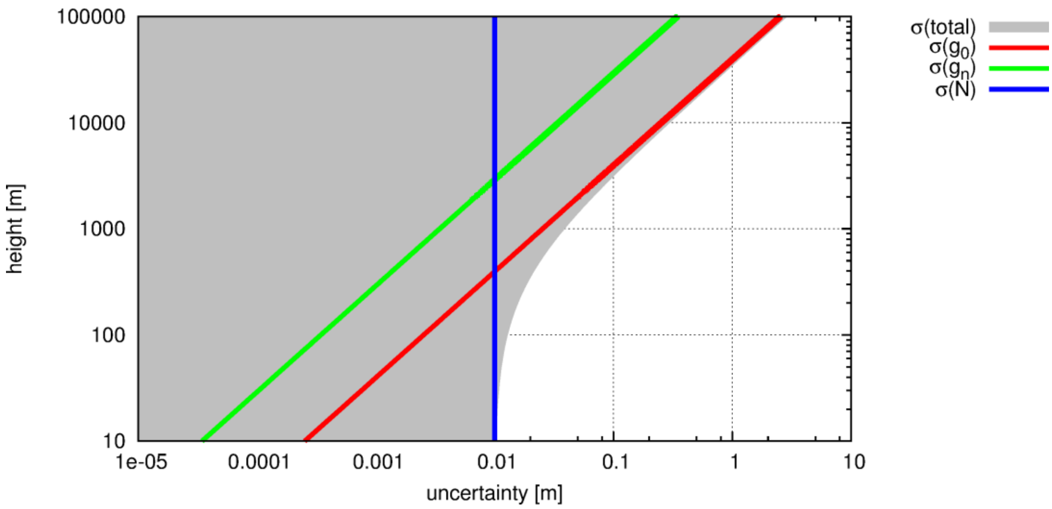

Figure 1: Uncertainties of σ(g_0), σ(norm) , σ(N) and the total error budget of the height transformation[Hobiger et al., 2012].

As shown in figure 0.4, the uncertainty of the geoid model, which results mostly from the geoid height (N), dominates the overall error budget in the lower height domains, i.e. <500 m. Above that height the choice of the gravity model and the way in which the mean gravity acceleration is computed becomes more important, and this error source starts to reduce the accuracy of the transformation. Thus, for a consistent and conventional height transformation between geopotential heights from a numerical weather model and ellipsoidal heights it is important that

- geoid heights are known with mm-accuracy on a global scale
- the gravity model provides both geoid heights and gravity acceleration at a given location
- the proper direction of the normal w.r.t. the reference figure is properly considered.

Fortunately, most of the atmospheric parameters relevant for geodesy (mainly pressure) decrease exponentially with height, which reduces the impact of an imperfect height transformation when performing an integration or summation in the vertical direction.
The study group agreed that a conventional vertical transformation be made available for users online, and we recommend it be provided in three programming languages (FORTRAN,

C/C++ and Matlab). Depending on the accuracy requirement and computational efforts, three different versions of the transformation should be provided.

1. A "conventional algorithm" based on EGM96 which transforms between the two systems. The model is expected to provide mean gravity as well as geoid height.
2. A "reduced algorithm" similar to (1) which uses a sub-set of the spherical harmonic coefficients. Source code should be available in the three programming languages and should aim at high performance for reduced accuracy applications.
3. A "simple algorithm" which is also available in the three programming languages. This algorithm is based on a (semi-) analytical expression for the gravity calculations and requires the user to input geoid heights manually.

Routines should be made available after the output from different programming languages has been checked for consistency, especially for model (1), which deals with high degree and order spherical harmonics.

Horizontal transformation

Based on various discussions it appears that horizontal coordinates in numerical weather models are equivalent to geodetic (WGS84 based) latitude/longitude pairs. Meteorologists deal with geodetic coordinates directly, i.e. they apply them on the sphere without any transformation. Although this method is straightforward for operational use, it might lead to some inconsistencies since the total volume of the atmosphere is changed. Thus, the study group drafted a document that lists questions concerning horizontal coordinates which need to be addressed to (by?) weather agencies. A draft version can be found in the appendix of this report for future reference.

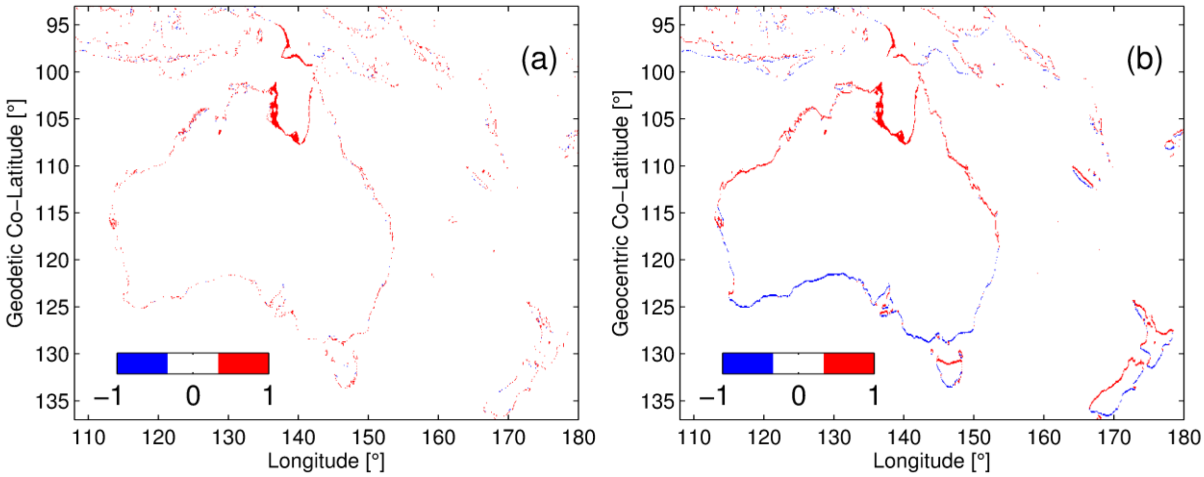

Figure 2: Land-sea-mask (LSM) differences between ETOPO2 and the operational ECMWF model as of April 2012 at a resolution of 6'. The ETOPO2 LSM was resampled from 2' to 6' using coordinate grids referred to (a) geodetic latitude and (b) geocentric latitude. Differences are shown in the sense 'ETOPO2 minus ECMWF'.

References and further reading:

T. Hobiger & the IAG ICCT SSG 0.4 members, Consistent height transformations between geodetic and meteorologic reference systems, 2012 AGU Fall Meeting, Dec. 3-7, 2012, San Francisco, USA.

B. N. Taylor, A. Thompson, The International System of Units, http://physics.nist.gov/Pubs/SP330/sp330.pdf, 2009.

Bibliography

J. Böhm, G.Möller, M. Schindelegger, G. Pain, R.Weber, Development of an improved empirical model for slant delays in the troposphere (GPT2w), GPS Solutions, doi: 10.1007/s10291-014-0403-7, 2015.

C. Desjardins, Tropospheric propagation modeling of satellite positioning system signals, Ph.D. Thesis, Université Toulouse III - Paul Sabatier, 2014, French. https://tel.archives-ouvertes.fr/tel-01131181

C. Desjardins, P. Gegout, L. Soudarin, R. Biancale, Rigorous interpolation of atmospheric state parameters for ray-traced tropospheric delays, Proceedings of the VIII Hotine-Marussi Symposium, International Association of Geodesy Symposia, vol. 142, accepted.

D. Eriksson, D. S. MacMillan, and J. M. Gipson, Tropospheric delay ray tracing applied in VLBI analysis, J. Geophys. Res. Solid Earth, vol. 119, iss. 12, pp. 9156-9170, doi:10.1002/2014JB011552, 2014.

T. Hobiger, D. Piester, and P. Baron, A correction model of dispersive troposphere delays for the ACES microwave link, Radio Science, vol. 48, iss. 2, pp. 131-142, 2013.

A. Hofmeister, J,Böhm, Ray-traced Delays in the Atmosphere for geodetic VLBI, IVS 2014 General Meeting Proceedings, ed. by Dirk Behrend, Karen D. Baver, and Kyla L. Armstrong, Science Press, Beijing, ISBN 978-7-03-042974-2, pp. 283-287, 2014.

Y. Kinoshita, M. Furuya, T. Hobiger, and R. Ichikawa, Are numerical weather model outputs helpful to reduce tropospheric delay signals in InSAR data?, Journal of Geodesy, vol. 87, iss. 3, pp. 267-277, 2013.

K. Lagler, M. Schindelegger, J, Böhm, H. Krásná, T. Nilsson, GPT2: Empirical slant delay model for radio space geodetic techniques, Geophys. Res. Lett., Vol. 40, pp. 1069–1073, doi:10.1002/grl.50288, 2013.

V. Nafisi, M. Madzak, J. Böhm, A,A. Ardalan, H. Schuh, Ray-traced tropospheric delays in VLBI analysis, Radio Science, Vol. 47, RS2020, doi:10.1029/2011RS004918, 2012.

V. Nafisi, L. Urquhart, M. Santos, F. Nievinski, J. Böhm, D. Wijaya, H. Schuh, A. Ardalan, T. Hobiger, R. Ichikawa, F. Zus, J. Wickert, P. Gegout, Comparison of Ray-Tracing Packages for Troposphere Delays, IEEE Transactions on Geoscience and Remote Sensing, Vol. 50, No. 2, pp. 469-481, 2012.

V. Nafisi, M. Madzak, J. Böhm, H. Schuh, A.A. Ardalan, Ray-traced tropospheric slant delays in VLBI analysis, Österreichische Zeitschrift für Vermessung und Geoinformation, Heft 2/2011, ISSN 1605-1653, Special Issue for the XXV General Assembly of the International Union of Geodesy and Geophysics (IUGG), Melbourne, Australia, edited by J. Böhm, A. Reiterer, F. Rottensteiner, H. Woschitz, pp. 149-153, 2011.

L. Urquhart, M. Santos, F .Nievinski, J. Böhm, Generation and Assessment of VMF1-Type Grids Using North-American Numerical Weather Models, Earth on the Edge: Science for a Sustainable Planet Proceedings of the IAG General Assembly, Melbourne, Australia, June 28 - July 2, 2011, Series: International Association of Geodesy Symposia, Vol. 139, edited by Chris Rizos and Pascal Willis, pp. 3-10, 2014.

Zus, F., G. Dick, J. Douša, S. Heise, and J. Wickert, The rapid and precise computation of GPS slant total delays and mapping factors utilizing a numerical weather model, Radio Sci., 49, 207–216, doi:10.1002/2013RS005280, 2014.

Appendix:

Questionnaire

IAG ICCT SSG member name:
Weather model:
Contact person(s) related to this model:

Brief description of the model:

Questions:
==========

(1) Vertical coordinate system

(1.1) What is the vertical coordinate system used by the model, and how does it relate to geometric height, pressure, or other parameters ?

(1.2) Are you using the standard value for gravity acceleration (9.80665 m/s^2)?

(1.3) What is the reference figure of your model? What is zero height? What is your understanding of the geoid?

(1.4) How do you geo-reference ground based measurements, balloon launches, etc? In particular how do you transform between ellipsoidal heights and model heights?

(1.5) Do you consider the Earth's oblateness?

(2) Horizontal coordinate system

(2.1) What is the horizontal coordinate system used by the model, and how does it relate to latitude and longitude?

(2.2) How is orography (topography dealt with)? In particular what is your understanding of latitudes (geocentric vs. geodetic)?

(2.3) How does this effect the inclusion of in-situ (ground based, balloons, etc.) data? How do you geo-reference a site/location properly? How do you geo-reference satellite data?

(2.4) If you use map projections, how is orography generated in your model and how can it be geo-referenced in a geodetic reference system?

(3) Miscellaneous

(3.1) Would you use a "conventional transformation" from/to geodetic reference systems if it is available?

(3.2) What are you accuracy requirements on such a transformation?

(3.3) Do you have any other requirements concerning the inclusion of data which has been geo-referenced in a geodetic coordinate system

(4) Other points discussed:

Please fill in here if you discussed something beyond (1) - (3)

Joint Study Group 0.5: Multi-Sensor Combination for the Separation of Integral Geodetic Signals

Chair: Florian Seitz (Germany)

1. Introduction and Objectives

This document presents the report of the work undertaken in the framework of the ICCT Joint Study Group JSG0.5 since its creation in 2011. Activities of the study group were focussed on the analysis and interpretation of observations from modern space-borne methods of Earth observation. A large part of the parameters derived from space geodetic observation techniques are integral quantities of the Earth system. Among the most prominent ones are parameters related to Earth rotation and the gravity field, whose variations reflect the superposed effect of a multitude of dynamic processes and interactions in various subsystems of the Earth. The integral geodetic quantities provide fundamental and unique information on different balances in the Earth system, in particular on the balances of mass and angular momentum that are directly related to (variations of) the gravity field and Earth rotation.

In respective balance equations, the geodetic parameters reflect the integrative effect of all mass- and angular momentum-related processes in the Earth system. For studies of suchlike processes, geodesy provides important input in the form of highly accurate parameter time series along with uncertainty information covering many decades. Variations of Earth rotation have even been determined for more than one and a half century using continuously improved astrometric and space geodetic observation techniques. Thus geodesy provides an excellent data base for the analysis of long term changes in the Earth system and contributes fundamentally to an improved understanding of large-scale processes.

However, in general the integral parameter time series cannot be separated into contributions of specific processes without further information. Their separation and therewith their geophysical interpretation requires complementary data from observation techniques that are unequally sensitive for individual effects and/or from numerical models. Activities of the study group were focussed on the development of strategies for the separation of the integral geodetic signals on the basis of modern space-based Earth observation systems. A multitude of simultaneously operating satellite systems with different objectives is available today. They offer a broad spectrum of information on global and regional-scale processes at different temporal resolutions. Research within the study group dealt with the question in which way the combination of heterogeneous data sets allows for the quantification of individual contributors to the balances of mass and angular momentum. The activities are coordinated between the participating scientists and conducted in interdisciplinary collaboration. The study group is primarily affiliated with IAG Commissions 2 (Gravity field) and 3 (Earth rotation and geodynamics).

2. Members

Chair:
Florian Seitz (Technische Universität München, Germany)

Full members:
Sarah Abelen (Germany)
Rodrigo Abarca del Rio (Chile)
Andreas Güntner (Germany)
Karin Hedman (Germany)
Franz Meyer (USA)

Michael Schmidt (Germany)
Manuela Seitz (Germany)
Alka Singh (India)

3. Report of Activities of the Study Group

The main results are related to the analysis and separation of Earth rotation and gravity field time series. The contributions of individual Earth system components (e.g., atmosphere, ocean, land hydrology) or even of particular dynamic processes (e.g., wind, ocean currents) were quantified and separated from the integral observed signals by means of specific data analysis methods (such as principle component analysis) or by the integration of complementary observation techniques and model data. The results have been presented in 12 joint reviewed journal publications and various conference contributions (talks and posters). Dedicated sessions at conferences were initiated and chaired by members of the study group. Among the most important and successful efforts were the joint application of two third-party funded projects in which five PhD students are working on topics related to the goals of the study group. They form a network with further PhD students and scientists at the participating institutions. Both projects are conducted in the frame of the International Graduate School of Science and Engineering (IGSSE) of the Technische Universität München (TUM).

The project CLIVAR-Hydro (*Signals of Climate Variability in Continental Hydrology from Multi-Sensor Space and In-situ Observations and Hydrological Modeling*) has been initiated in 2010 (http://www.dgfi.tum.de/en/projects/clivar-hydro/) and provides funds for three PhD students. CLIVAR-Hydro aims to perform a multi-sensor approach in order to detect, separate and balance individual contributions to continental water storage variations for selected large river basins. A specific focus of the study is on the analysis of climate signals. The project exploits the synergies of various observation systems and combines their output with hydrological simulation models. The project is carried out within a largely interdisciplinary group of networking scientists and PhD students from space engineering, geodesy, hydrology and climate research. It provides new and valuable insights into hydrological processes and the impacts of climate change on the global water cycle.

A follow-up project for two additional PhD positions has been developed in collaboration between members of JSG0.5. The project REWAP (*Monitoring and Prediction of Regional Water Availability for Agricultural Production under the Influence of Climate Anomalies and Weather Extremes*) started in 2014 (http://www.dgfi.tum.de/en/projects/rewap/). It addresses one of the most important issues facing humanity during this century, i.e., the threat posed by hydrological impacts on agricultural production under climate change. The principal task of the project is to investigate, in which way and with which consequences time-variable hydrological conditions are linked to regional water availability. Of particular interest is the question, in which way changes in regional conditions occur in response to large-scale phenomena in the global climate system. Using up-to-date satellite technology, in particular the twin-satellite gravity field mission GRACE, the project aims at monitoring suchlike large-scale phenomena and – in combination with ground and model data – forecasting their impact to regional-scale hydrological and agricultural conditions.

Members of the JSG0.5 performed mutual research visits at the institutions involved, where they worked together for several months in the frame of the common projects. The exchange of personnel between the institutions was financed through project funds. From March until November 2013 a PhD student of the Universidad de Concepción worked at DGFI/TUM in the field of GRACE data analysis. From January to February 2014 Sarah Abelen joined the group in Chile and worked towards the separation of the soil moisture component in GRACE observations. Rodrigo Abarca del Rio (Chile) joined DGFI/TUM in October 2014 for discussions about the interpretation of variations of Earth rotation and the gravity field. This mobility contributed significantly to the cross-linked collaboration within JSG0.5.

3.1. Publications of SG Members

Abelen, S., F. Seitz, R. Abarca del Rio, A. Güntner: Droughts and floods in the La Plata basin in soil moisture data and GRACE. Remote Sensing, in press.

Göttl, F., M. Schmidt, F. Seitz, M. Bloßfeld: Separation of atmospheric, oceanic and hydrological polar motion excitation mechanisms based on a combination of geometric and gravimetric space observations. J. Geodesy, 89, 377-390, 2015.

Seitz, F., Hedman, K., Meyer, F., Lee, H.: Multi-sensor space observation of heavy flood and drought conditions in the Amazon region. In: Rizos, C., Willis, P. (eds.) Earth on the Edge: Science for a Sustainable Planet, IAG Symposia, Vol. 139, 311-318, Springer, 2014.

Singh, A., Seitz, F., Schwatke, C.: Application of multi-sensor satellite data to observe water storage variations. J. Selected Topics in Applied Earth Obs. and Remote Sens., 6, 1502-1508, doi: 10.1109/JSTARS.2013.2258326, 2013.

Abelen, S., Seitz, F.: Relating satellite gravimetry data to global soil moisture products via data harmonization and correlation analysis. Remote Sensing of Environ., 136, 89-98, 2013.

Schnitzer, S., Seitz, F., Eicker, A., Güntner, A., Wattenbach, W., Menzel, A.: Estimation of soil loss by water erosion in the Chinese Loess Plateau using Universal Soil Loss Equation and GRACE. Geophys. J. Int., 193, 1283-1290, 2013.

Singh, A., Seitz, F.: Water Storage Variations in the Aral Sea from Multi-sensor Satellite Data in comparison with Results from GRACE gravimetry. IEEE International Geoscience and Remote Sensing Symp. (IGARSS), 3042-3045, 2012.

Schmeer, M., Schmidt, M., Bosch, W., Seitz, F.: Separation of mass signals within GRACE monthly gravity field models by means of empirical orthogonal functions. J Geodynamics, 59, 124-132, 2012.

Seitz, F., Kirschner, S., Neubersch, D.: Determination of the Earth's Pole Tide Love Number k2 from Observations of Polar Motion Using an Adaptive Kalman Filter Approach. J. Geophysical Research, Vol. 117, Nr. B09, EID B09403, 2012.

Singh, A., Seitz, F., Schwatke, C.: Inter-annual water storage changes in the Aral Sea from multi-mission satellite altimetry, optical remote sensing, and GRACE satellite gravimetry. Remote Sensing of Environ., 123, 187-195, 2012.

Seitz, F., Thomas, M.: Simulation, prediction and analysis of Earth rotation parameters with a dynamic Earth system model. in: Schuh, H., et al. (eds.) Proc. "Journées 2011 Systèmes de Référence Spatio-temporels", 109-112, TU Wien, 2012.

Abelen, S., Seitz, F., Schmidt, M., Güntner, A.: Analysis of regional variations in soil moisture by means of remote sensing, satellite gravimetry and hydrological modelling. In: Hafeez, M., et al. (eds.) GRACE, Remote Sensing and Ground-based Methods in Multi-Scale Hydrology, IAHS Red Book Series, Nr. 343, 9-15, 2011.

3.2. Selected Conference Contributions of SG Members

Ressler, G., Eicker, A., Lieb, V., Schmidt, M., Seitz, F., Shang, K., Shum, C.K.: Water storage variations extracted from GRACE data by combination of multi-resolution representation (MRR) and principal component analysis (PCA). EGU GA, Vienna, Austria, 16.4.2015.

Baumann, S., Menzel, A., Seitz, F., Güntner, A., Abelen, S.: Comparison of measured glacier mass balance data in the Tian Shan and Pamir Mountains, Central Asia, with GRACE satellite gravimetry. International Symposium on Glaciology in High-Mountain Asia, Kathmandu, Nepal, 2.-6.3.2015.

Abelen, S., Schnitzer, S., Singh, A., Seitz, F., Abarca del Rio, R., Güntner, A.: How heavy are extreme weather events? WCRP-ICTP Summer School on Attribution and Prediction of Extreme Events, Trieste, Italy, 21.7.2014.

Göttl, F., Schmidt, M., Seitz, F., Bloßfeld, M.: Separation of atmospheric, oceanic and hydrological polar motion excitation by a combination of geometric and gravimetric space observations. EGU GA, Vienna, Austria, 29.4.2014.

Abelen, S.; Seitz, F.: Relating global soil moisture data to total continental water storage; Satellite Soil Moisture Validation and Application Workshop, Frascati, ESA ESRIN, 02.07.2013

Singh, A., Seitz, F., Schwatke, C., Güntner, A.: Hydrological storage variations in a lake water balance, observed from multi-sensor satellite data and hydrological models. EGU GA, Vienna, Austria, 11.4.2013.

Seitz, F., Kirschner, S., Neubersch, D.: Polar motion as boundary condition in an adaptive Kalman Filter approach for the determination of period and damping of the Chandler oscillation. AGU 2012 Fall Meeting, San Francisco, USA, 07.12.2012 (invited).

Seitz, F., Hedman, K.: Towards the Separation of Integral GRACE Signals of Continental Water Storage Using Multi-Sensor Space and In-situ Observations. AGU 2012 Fall Meeting, San Francisco, USA, 06.12.2012.

Seitz, F., Hedman, K., Spiridonova, S.: Intersection of SAR imagery with medium resolution DEM for the estimation of regional water storage changes. German Geodetic Week, Hannover, 10.10.2012.

Singh, A., Seitz, F., Schwatke, C., Bosch, W.: Application of the Satellite Altimetry over Terrestrial Water Body: A Case Study on Aral Sea. 20 Years of Progress in Radar Altimetry, Venice, Italy, 25.09.2012.

Seitz, F., Kirschner, S.: Application of Earth rotation parameters in Earth system science. IAU XXVIII GA, Beijing, 30.08.2012.

Seitz, F.: Understanding Earth Rotation: Physical Foundations and Interpretation. International Summer School on Space Geodesy and Earth System, Shanghai, 23.08.2012.

Singh, A., Seitz, F.: Water storage variations in the Aral Sea from multi-sensor satellite data in comparison with results from GRACE gravimetry. IGARSS, Munich, 25.07.2012.

Singh, A., Seitz, F., Schwatke, C.: Observations of Water Storage Variations in the Aral Sea from Multi-sensor Satellite data. 2nd IAHR Europe Congress, Munich, 28.06.2012.

Seitz, F., Göttl F., Heiker A., Kirschner S., Kutterer H., Schmidt M.: Combination of geodetic observations and geophysical models for estimating consistent Earth rotation and gravity field parameters, individual excitation mechanisms and physical Earth parameters. EGU GA, Vienna, Austria, 22.-27.4.2012.

Singh, A., Seitz, F., Schwatke, C., Güntner, A.: Geometrical and gravimetrical observations of the Aral Sea and its tributaries along with hydrological models. EGU GA, Vienna, Austria, 23.4.2012.

Spiridonova, S., Seitz, F., Hedman, K., Meyer, F.: Water mass change in the Amazon basin estimated by multi-temporal SAR data, GRACE gravimetry and water level observations. EGU GA, Vienna, Austria, 22.-27.4.2012.

Abelen, S., Seitz, F., Güntner, A.: Global comparison of soil moisture variations as derived from remote sensing, satellite gravimetry, and hydrological modeling. EGU GA, Vienna, 25.04.2012.

Seitz, F., Kirschner, S.: Simulation, prediction and analysis of polar motion with a dynamic Earth system model. EGU GA, Vienna, 23.04.2012.

Seitz, F., Abelen, S., Singh, A., Schnitzer, S.: Compartmental water storage changes from multi-sensor data and their signatures in GRACE observations. SPP 1257 Workshop on GRACE-Hydrology, Bonn, 13.02.2012.

Singh, A., Seitz, F., Schwatke, C.: Inter-annual water storage changes in the Aral Sea from multi-mission satellite altimetry, remote sensing and GRACE satellite gravimetry. German Geodetic Week 2011, Nuremberg, 28.09.2011.

Rinner, C., Seitz, F., Abelen, S.: Comparison of soil moisture products of the sensors AMSR-E and MIRAS. German Geodetic Week 2011, Nuremberg, 28.09.2011.

Seitz, F.: Simulation, prediction and analysis of Earth rotation parameters with a dynamic Earth system model. Journées "Systèmes de référence spatio-temporels", Vienna, 20.09.2011.

Abelen, S., Seitz, F., Güntner, A., Schmidt, M.: Analysis of regional variations in soil moisture by means of remote sensing, satellite gravimetry and hydrological modeling. IUGG XXV GA, Melbourne, 05.07.2011.

Seitz, F., Schmidt, M., Shum, C.K., Hedman, K., Lee, H., Meyer, F.: Multi-sensor space and in-situ monitoring of extreme hydrological conditions in the Amazon region. IUGG XXV GA, Melbourne, 03.07.2011.

Abelen, S., Seitz, F., Güntner, A., Schmidt, M.: Signals of soil moisture variations in remote sensing and gravity field observations. IUGG XXV GA, Melbourne, 02.07.2011.

Seitz, F.: Multi-sensor space and in-situ observations for the separation of integral GRACE signals of continental water storage. EGU GA, Vienna, Austria, 7.4.2011.

Seitz, F., Kutterer H., Schmidt M., Kirschner, S., Heiker A., Göttl F.: Estimation of Earth rotation and gravity field parameters, separated excitation mechanisms and physical Earth parameters from geometric and gravimetric space observations. EGU GA, Vienna, Austria, 6.4.2011.

3.3. Study group web page

The webpage of the group is http://icct.kma.zcu.cz/index.php/IC_SG5

3.4. Conference Sessions

EGU General Assembly, Vienna:
2012, April 23: Session G5.1, Observing and understanding Earth rotation variability and its geophysical excitation (Convenor: F. Seitz): 12 oral presentations, 18 posters.

2013, April 8: Session G3.3, Observing and understanding Earth rotation variability and its geophysical excitation (Convenor: F. Seitz): 6 oral presentations, 10 posters.

2014, April 29/30: Session G3.3, Earth Rotation: Theoretical aspects, observation of temporal variations and physical interpretation (Convenor: F. Seitz): 6 oral presentations, 16 posters.

2015, April 15: Session G3.4, Earth Rotation: Theoretical aspects, observation of temporal variations and physical interpretation (Co-Convenor: F. Seitz): 6 oral presentations, 12 posters.

IAU General Assembly, Beijing:
2012, August 29/30: Science Meeting of IAU Commission 19 – Rotation of the Earth (Convenor: F. Seitz): 10 oral presentations.

INTERGEO/German Geodetic Week:
2011, September 28, Nuremberg: Session 5: GGOS – Global Geodetic Observing System (Convenor: F. Seitz): 6 oral presentations.

2012, October 11, Hanover: Session 5: GGOS – Global Geodetic Observing System (Co-Convenor: F. Seitz): 5 oral presentations.

2013, October 9/10, Essen: Session 5: GGOS – Global Geodetic Observing System (Co-Convenor: F. Seitz): 9 oral presentations.

2014, October 7, Berlin: Session 5: GGOS – Global Geodetic Observing System (Co-Convenor: F. Seitz): 7 oral presentations.

Joint Study Group 0.6: Applicability of Current GRACE Solution Strategies to the Next Generation of Inter-Satellite Range Observations

Chairs: Matthias Weigelt (Germany), Adrian Jäggi (Switzerland)

The main objective of this study group is the preparation and testing of existing solution strategies for their applicability to the upcoming GRACE-Follow On and future satellite missions. These missions will be equipped with improved instruments such as the laser interferometer (LRI). Since existing solution strategies make use of linearization and/or depend on augmentation with other observed quantities, e.g. GPS, it needs to be tested if existing solution strategies are suitable to take full advantage of the offered precision.

Simulation of observations:

The creation of simulated data sets, which are applicable to theoretical questions but offer also a great deal of realism at the same time, is the first and a very demanding task. The group opted for two data sets: (1) for theoretical questions use was made of the SC7 data set, which has been developed by a team led by the University of Bonn in 2003, and (2) a second data set was prepared by Jean-Claude Raimondo and colleagues at the German Research Centre for Geoscience in Potsdam and is based on orbit integration of the static gravity field EIGEN-GL04C up to degree and order 90 but includes also solid Earth and ocean tides, geophysical effects inducing a time variable gravity signal or non-gravitational forces. Details are listed in table 1.

Table 1: Models included in the preparation of the simulated data set with a high degree of realism

Source	**Implementation**
Static gravity field	EIGEN-GL04C up to 90x90
Planetary Ephemerides	JPL DE405 - only Sun and Moon
Ocean tides	EOT08a up to 50x50 only 8 waves: Q1, O1, P1, K1, N2, M2, S2, K2
Time variable gravity field	AOHIS ESA model up to 90x90
Non-gravitational accelerations	atmospheric drag, solar radiation pressure, Earth albedo and infra-red radiation (also provided separately)

Both data set are prepared for 30 days and with a five second sampling. Satellite-specific as well as inter-satellite quantities are provided including attitude information for both satellites.

The second important step is the preparation of realistic noise time series for the various simulated sensors, e.g. the inter-satellite K-Band and LRI observations. These noise time series are only prepared for the second data set at the moment. One types of noise data set has been prepared in the framework of the "BMBF-Geotechnologien" program "Zukunftskonzepte für Schwerefeldmissionen" and is kindly made available to members of this study group (thanks to Phillip Brieden).

Investigations on the acceleration approach for the llSST-case

Theoretical investigations focused primarily on the acceleration approach being one that incorporates GPS-observations in the mathematical model. Using the observations as is results in a mixture of the poorer precision of GPS-observations with the K-Band information. One common way to reach a solution has been to reduce the observations to residual quantities using *a priori* information and subsequently solving for corrections to the used *a priori* gravity field model neglecting the GPS-related term (a.k.a. crosstrack or radial term). Investigations showed that this approximation is even for the current GRACE K-Band solutions insufficient. The approach therefore needs to be refined by considering the residual radial term which requires the solution of the variational equations. Due to the distinct spectral behaviour the development for this second term can be limited to a very low degree (10), i.e. the computational burden can be significantly reduced. The relation between the relative gravity gradient projected on the line of sight and the range-observations cannot be considered as an in-situ approach anymore but solutions are on the same level of precision as existing GRACE solutions of the processing centres.

As it was the idea of the acceleration approach to be an in-situ approach, alternatives have been investigated and one possibility has been found by developing the radial term in terms of rotational quantities. This has been successfully achieved and the new formulation allows for considerable insight into the nature of the satellite observation system, e.g. an analytical explanation for the poor East-West observability of GRACE is at hand now. Investigations on the provided precision of the star cameras showed that they currently insufficient but the upcoming LRI will provide a new technology called differential wavefront sensing which may allow the exploitation of the approach.

Activities related to the Gravity Recovery And Interior Laboratory (GRAIL) mission

The Gravity Recovery And Interior Laboratory (GRAIL) mission orbiting the Moon and the Gravity Recovery And Climate Experiment (GRACE) mission orbiting the Earth share many conceptual commonalities. Major differences reside, however, in the absolute positioning of the spacecraft, which is accomplished by Doppler tracking from NASA's Deep Space Network (DSN) for GRAIL and by the Global Positioning System (GPS) for GRACE. Data from GRACE and from the Gravity and steady-state Ocean Circulation Explorer (GOCE) has been used to investigate the role of position information. Artificially degrading either the geographical coverage or the accuracy of kinematic positions serving as input data together with continuously available K-Band inter-satellite data is found not to be a limiting factor for gravity field recovery using the Celestial Mechanics Approach (CMA). Eventually, the CMA has been applied to Level-1B data of the GRAIL mission deriving first Bernese lunar gravity field solutions.

Organisational and other achievements

Besides the technical progress also other activities have been successfully accomplished. The members of the group assigned themselves to various workgroups allowing for a structured approach to the various objectives of the study group. The exchange of information and knowledge has been fostered, e.g. a literature list with the most important and relevant publications for the investigated approaches has been compiled and made available to the members of the group. Group members are updated about the developments within the group by means of the internal newsletter "JSG0.6 Circular". Most importantly, one of the largest sessions at the VIII Hotine-Marussi Symposium in Rome in June 2013 has been successfully organized whereas eleven presentations were related to JSG0.6 activities. Gerhard Beutler and Christoph Dahle gratefully agreed to give invited presentations. A number of publications stemming from these presentations were also submitted to the upcoming proceedings of the meeting.

Experiences

As requested by ICCT a short feedback on the management and experiences throughout the last four years is given. The chairs are very grateful to the commitment of the group members and quite some work has been achieved.

The primary concern is that this commitment is based on voluntary contributions, which means that these activities will always have a lower priority than ongoing project- or thesis-work. Delays and slow progress are the natural consequence. It is emphasized that it is not due to a lack of willingness or commitment by group members but rather a question of priority. ICCT and IAG needs to consider how to support the activities under their umbrella and how to stimulate advancement. This could for example be achieved by financial support or waivers for publications fees which in turn will allow members of the JSG to assign a higher priority to the activity. After all, activities often need to be justified to supervisors and/or other authorities. Furthermore a more active role of ICCT and IAG in these activities should be considered. Contrary to the activity itself, the benefit to do the work within the umbrella of ICCT and IAG is not obvious to members on the one hand and outsiders on the other hand. IAG and ICCT should therefore consider to develop and evolve their framework of support.

Another major point of concern is the again long delay in the publication of the Hotine-Marussi proceedings. Already for the VII Hotine-Marussi proceedings it took more than three years and the current one is still not published although nearly two years have been passed since the meeting. It will be increasingly difficult to motivate people to contribute to the meeting and the proceedings if delays continue to exist.

Joint Study Group 0.7: Computational Methods for High-Resolution Gravity Field Modelling and Nonlinear Diffusion Filtering

Chairs: Róbert Čunderlik, Karol Mikula (Slovakia)

Activities of the JSG-0.7 have been mainly focused on development of new approaches for high-resolution gravity field modelling and nonlinear diffusion filtering using efficient numerical methods, namely the boundary element method (BEM), finite volume method (FVM), method of fundamental solution (MFS) or singular boundary method (SBM). Most of the achieved results were presented mainly in geodetic conferences, e.g. the GGHS-2012 symposium in Venice (October 2012), EGU-2013, EGU-2014 and EGU2015 in Wien, IAG-2013 in Potsdam (September 2013) or IGFS-2014 in Shanghai (July 2014). In addition, our JSG was organizing the session "Computational geodesy" within the VIII Hotine-Marussi Symposium in Roma (June 2013) that included 5 oral presentations and 3 posters. The results achieved by our JSG have been also published in the journal papers or proceedings from the IAG Symposia. Below is a more detail description of our activities.

High-resolution gravity field modelling

Boundary element method

In case of the developed parallel approach by BEM, which considers real topography of the Earth's surface, the problem of oblique derivative has been investigated. There have been proposed and tested algorithms where the oblique derivative is decomposed to normal and tangential components. The numerical experiments have been applied for high-resolution global gravity field modelling as well as for precise local modelling using discrete terrestrial gravimetric measurements, e.g. in Slovakia and New Zealand.

Finite volume method

There have been proposed and developed new approaches by FVM for global and local modelling. The parallel implementation using the MPI procedures and large-scale parallel computations on clusters with distributed memory has resulted in the global FVM solutions with the horizontal resolution corresponding to the spherical harmonics (SH) up to degree 2160 (like EGM2008). The FVM approach has been successfully applied for local modelling as well. Later the problem of oblique derivative has been incorporated in the proposed numerical schemes. The FVM numerical scheme for the nonlinear geodetic BVP has been derived as well. The FVM approach has been also applied to solve the altimetry-gravimtery BVP. It has resulted in high-resolution modelling of the altimetry-derived gravity data over oceans.

Method of fundamental solutions and singular boundary method

There has been developed new approach by MFS for global gravity field modelling. This approach based on the point masses modelling has been proposed to process the GOCE gravity gradients. The developed algorithm has been designed to derive the disturbing potential or its derivatives from the T_{rr} radial components available from the SGG_TRF_2 product. The numerical experiments have studied how a depth of the fictitious boundary, where the source points are located, influences accuracy of the achieved results. Ideas of SBM have been applied in case that the source points are located directly on the Earth's surface.

Such ideas are based on appropriate regularization techniques that isolate singularities of the fundamental solution or its derivatives. A parallel implementation of algorithms, iterative elimination of far zones' interactions and large-scale computations has yielded an efficient tool for gravity field modelling from the GOCE observations while solving the problem in a space domain. Processing of all available GOCE data has resulted in the static GOCE-based global gravity field model. It has been used to evaluate the geopotential on the mean sea surface models leading to the W_0 estimates that are independent from ones obtained by the SH-based methods.

Nonlinear diffusion filtering

There have been proposed and developed new approaches for linear and nonlinear diffusion filtering on a closed surface like a sphere, ellipsoid or the triangulated approximation of the real Earth's surface. The surface FVM have been used to derive an implicit numerical scheme for the linear diffusion and semi-implicit numerical schemes for the nonlinear diffusion equations on such closed surfaces. Two nonlinear models have been considered. In case of the Perona-Malik model, which is suitable for reducing an additive noise, the developed method has been applied for filtering various data, e.g., the satellite-only mean dynamic topography or the direct GOCE measurements. This model as well as numerical experiments has been published in Journal of Geodesy (2013, Vol. 87). Another nonlinear filtering model based on the geodesic mean curvature flow, which is suitable for reducing noise of the type "salt & papper", has been recently proposed and developed. It will be presented during the IUGG-2015 General Assembly in Prague.

Publications

Journal Papers

Čunderlík R, Mikula K, Tunega M (2013) Nonlinear diffusion filtering of data on the Earth's surface. Journal of Geodesy, Vol. 87(2), pp. 143-160

Holota P, Nesvadba O (2014) Reproducing kernel and Neumann's function for the exterior of an oblate ellipsoid of revolution: application in gravity field studies. Studia Geophysica et Geodaetica, Vol. 58(4), pp. 505-535

Macák M, Minarechová Z, Mikula K (2014) A novel scheme for solving the oblique derivative boundary-value problem. Studia Geophysica et Geodaetica, Vol. 58(4), pp. 556-570

Minarechová Z, Macák M, Čunderlík R, Mikula K (2015) High-resolution global gravity field modelling by the finite volume method. Studia Geophysica et Geodaetica, Vol. 59(1), pp. 1-20

Eymard R, Handlovicova A, Herbin R, Mikula K, Stasova O (2015) Applications of approximate gradient schemes for nonlinear parabolic equations, Applications of Mathematics, Vol. 60(2), pp. 135-156

IAG Symposia Series

Čunderlík R, Fašková Z, Mikula K (2012) Fixed gravimetric BVP for the vertical datum problem. In: Geodesy for planet Earth. IAG Symp, Vol. 136 , pp. 333-341

Holota P, Nesvadba O (2012) On a Combined use of satellite and terrestrial data in Refined studies on earth gravity field: Boundary problems and a target function. In: Geodesy for planet Earth. IAG Symp, Vol. 136 , pp. 195-204

Čunderlík R, Mikula K, Špir R (2012) An oblique derivative in the direct BEM formulation of the fixed gravimetric BVP. In: VII Hotine-Marussi Symposium on Mathematical Geodesy. IAG Symp, Vol. 137, pp. 227-231

Fašková Z, Čunderlík R, Mikula K, Tenzer R (2013) Influence of Vertical Datum Inconsistencies on Gravity Field Modelling. In: Reference Frames for Applications in Geosciences, IAG Symp, Vol. 138, pp. 205-213

Abdalla A, Tenzer R (2014) The integral-equation-based approaches for modelling the local gravity field in the remove–restore scheme. In: IAG Symp, Vol. 139, pp. 283-289

Čunderlík R, Tenzer R, Mikula K (2014) Realization of WHS based on gravity field models free of dependencies on local vertical datums. In: Gravity, Geoid and Height Systems, GGHS 2012, IAG Symp, Vol. 139, pp. 551-559

Čunderlík R, Minarechová Z, Mikula K (2014) Realization of WHS based on the static gravity field observed by GOCE. In: Gravity, Geoid and Height Systems, GGHS 2012, IAG Symp, Vol. 141, pp. 211-220

Sánchez L, Dayoub N, Čunderlík R, Minarechová Z, Mikula K, Vatrt V, Vojtíšková M, Šíma M (2014) W0 Estimates in the Frame of the GGOS Working Group on Vertical Datum Standardisation. In: Gravity, Geoid and Height Systems, GGHS 2012, IAG Symp, Vol. 141, pp. 203-210

Čunderlík R (2015) Determination of W0 from the GOCE measurements using the method of fundamental solutions. In: VIII Hotine-Marussi Symposium on Mathematical Geodesy. IAG Symp, Vol. 142, (in press, accepted in October 2013)

Macák M, Mikula K, Minarechová Z, Čunderlík R (2015) On an iterative approach to solving the nonlinear satellite-fixed geodetic boundary-value problem In: VIII Hotine-Marussi Symposium on Mathematical Geodesy. IAG Symp, Vol. 142, (in press, accepted in November 2013)

Nesvadba O, Holota P (2015) An OpenCL implementation of ellipsoidal harmonics. In: VIII Hotine-Marussi Symposium on Mathematical Geodesy. IAG Symp, Vol. 142, (in press, accepted in January 2014)

Čunderlík R (2015) Precise modelling of the static gravity field from the GOCE data using the method of fundamental solutions. In: Proceedings of the IGFS-2014. IAG Symp, (submitted in October 2014)

Others

Čunderlík R, Mikula K (2015) Nonlinear diffusion filtering of the GOCE-based satellite-only mean dynamic topography. In: The 5th international GOCE user workshop, ESA, 25-29 November 2014, UNESCO Headquarter, Paris, France, ESA-Proceedings (CD version)

Joint Study Group 0.8: Earth System Interaction from Space Geodesy

Chair: Shuanggen Jin (China)

Introduction

The gravity field and geodetic mass loading reflect mass redistribution and transport in the Earth's fluid envelope, and in particular interactions between atmosphere, hydrosphere, cryosphere, land surface and the solid Earth due to climate change and tectonics activities, e.g., dynamic and kinematic processes and co-/post-seismic deformation. However, the traditional ground techniques are very difficult to obtain high temporal-spatial resolution information and processes, particularly in Tibet. With the launch of the Gravity Recovery and Climate Experiment (GRACE) mission since 2002, it was very successful to monitor the Earth's time-variable gravity field by determining very accurately the relative position of a pair of Low Earth Orbit (LEO) satellites. Therefore, the new generation of the gravity field derived from terrestrial and space gravimetry, provides a unique opportunity to investigate gravity-solid earth coupling, physics and dynamics of the Earth's interior, and mass flux interaction within the Earth system, together with GPS/InSAR.

Objectives

- To quantify mass transport within the Earth's fluid envelope and their interaction in the Earth system.
- To monitor tectonic motions using gravimetry/GPS, including India-Tibet collision, post-glacial uplift and the deformation associated with active tectonic events, such as earthquakes and volcanoes.
- To develop inversion algorithm and theories in a Spherical Earth on gravity field related deformation and gravity-solid Earth coupling, e.g. crust thickness, isostatic Moho undulations, mass loadings and geodynamics.
- To develop methods to extract a geodynamic signals related to Solid-Earth mantle and/or core and to understand the physical properties of the Earth interior and its dynamics from the joint use of gravity data and other geophysical measurements.
- To analyze and model geodynamic processes from isostatic modelling of gravity and topography data as well as density structure of the Earth's deep interior.
- To address mantle viscosity from analyzing post-seismic deformations of large earthquakes and postglacial rebound (PGR) and to explain the physical relationships between deformation, seismicity, mantle dynamics, lithospheric rheology, isostatic response, etc.
- To achieve these objectives, the IC SG interacts and collaborates with the ICCT and all IAG Commissions.

Activities

2015

- **12-17 April 2015**, Shuanggen Jin was Session Co-Convener, European Geosciences Union (EGU) General Assembly, Vienna, Austria.

2014

- **15-18 December 2014**, Shuanggen Jin was Session Co-Convener, AGU Fall Meeting, San Francisco, USA.
- **1-11 August 2014**, Shuanggen Jin attended the 40th COSPAR Scientific Assembly as Session Chair with one invited talk, Moscow, Russia.

- **22-26 July 2014**, Shuanggen Jin was Member of Scientific Organizing Committee and Session Chair at International Symposium on Geodesy for Earthquake & Natural Hazards, Miyagi, Japan.
- **20 January 2014**, Shuanggen Jin organized Workshop on Water Cycle Observation from Space at Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai, China.

2013

- **13-16 October 2013**, Shuanggen Jin attended the 29th Annual Meeting of Chinese Geophysical Society (CGS) with receiving Liu Guangding Geophysical Youth Science and Technology Award, Kunming, China.
- **1-11 September 2013**, Shuanggen Jin attended International Association of Geodesy (IAG) Scientific Assembly (IAG2013) with two oral talks and five session chairs in Potsdam, Germany and visited University of Beira Interior (UBI) and University of Lisbon with one talk, Lisbon, Portugal.

2012

- **12 December 2012**, Shuanggen Jin, Per Knudsen and Ole Andersen co-organized SHAO-DTU Workshop on Space Geodesy and discussed future possible collaboration, Shanghai, China
- **18-21 August 2012**, Shuanggen Jin organized International Symposium on Space Geodesy and Earth System (SGES2012) as Chair of Symposium, Shanghai, China.
- **21-25 August 2012**, Shuanggen Jin organized International Summer School on Space Geodesy and Earth System, Shanghai, China

2011

- **10-18 November 2011**, Shuanggen Jin was invited to visit and give several talks at Taiwan National Chiao Tung University, National Cheng Kung University, National Central Univesity and Institute of Earth Sciences, Academia Sinica, Taiwan.

Selected Publications

Zhang, Y., J. Yan, F. Li, C. Chen, B. Mei, S.G. Jin, and J.H. Dohm (2015), A new bound constraint method for 3D potential field data inversion using Lagrangian multipliers, Geophys. J. Int., 201(1), 267-275, doi: 10.1093/gji/ggv016.

Tenzer, R., W. Chen, and S.G. Jin (2015), Effect of the upper mantle density structure on the Moho geometry, Pure Appl. Geophys., doi: 10.1007/s00024-014-0960-2.

Tenzer, R., W. Chen, D. Tsoulis, M. Bagherbandi, L. Sjoberg, P. Novak, and S.G. Jin (2015), Analysis of the refined CRUST1.0 crustal model and its gravity field, Surv. Geophys., 36(1), 139-165, doi: 10.1007/s10712-014-9299-6.

Li, F., J.G. Yan, L.Y. Xu, S.G. Jin, J. A. Rodriguez, and J.H. Dohm (2015), A 10 km-resolution gravity field model of Venus based on topography, Icarus, 247, 103-111, doi: 10.1016/j.icarus.2014.09.052.

Jin, S.G., and X.G. Zhang (2014), A Tikhonov regularization method to estimate Earth's oblateness variations from global GPS observations, J. Geodyn., 79, 23-29, doi: 10.1016/j.jog.2014.04.011.

Jin, S.G., T. van Dam, and S. Wdowinski (2013), Observing and understanding the Earth system variations from space geodesy, J. Geodyn., 72, 1-10, doi: 10.1016/j.jog.2013.08.001.

Jin, S.G., and G. Feng (2014), Global groundwater cycles and extreme events responses observed by satellite gravimetry, in U. Marti et al. (Eds.), IAG Symposia Book Series: Gravity, Geoid and Height Systems (GGHS2012), Venice, Italy, 9-12 October 2012, Springer Verlag, Heidelberg, Germany, pp.283-288, doi: 10.1007/978-3-319-10837-7_36.

Jin, S.G., T. van Dam, and S. Wdowinski (Eds.) (2013), Earth System Observing and Modelling from Space Geodesy, Special Issue in Journal of Geodynamics, Elesvier, ISSN: 0264-3707, 72, pp. 1-94.

Jin, S.G. (2013), Satellite Gravimetry: Mass Transport and Redistribution in the Earth System, in S.G. Jin (Ed.), Geodetic Sciences: Observations, Modeling and Applications, InTech-Publisher, Rijeka, Croatia, ISBN: 980-953-307-595-7, pp.

Jin, S.G. (2013), GNSS Observations of Crustal Deformation: A Case Study in East Asia, in S.G. Jin (Ed.), Geodetic Sciences: Observations, Modeling and Applications, InTech-Publisher, Rijeka, Croatia, ISBN: 980-953-307-595-7, pp.

Jin, S.G., and G. Feng (2013), Large-scale variations of global groundwater from satellite gravimetry and hydrological models, 2002-2012, Global Planet. Change, 106, 20-30, doi: 10.1016/j.gloplacha.2013.02.008.

Wei, E., W. Yan, S.G. Jin, J. Liu, and J. Cai (2013), Improvement of Earth orientation parameters estimate with Chang'E-1 ⊿VLBI Observations, J. Geodyn., doi: 10.1016/j.jog.2013.04.001.

Feng, G., S.G. Jin, and T. Zhang (2013), Coastal sea level changes in the Europe from GPS, Tide Gauge, Satellite Altimetry and GRACE, 1993-2011, Adv. Space Res., 51(6), 1019-1028, doi: 10.1016/j.asr.2012.09.011.

Jin, S.G., A. Hassan, and G. Feng (2012), Assessment of terrestrial water contributions to polar motion from GRACE and hydrological models, J. Geodyn., 62, 40-48, doi: 10.1016/j.jog.2012.01.009.

Zhang, L., S.G. Jin, and T. Zhang (2012), Seasonal variations of Earth's surface loading deformation estimated from GPS and satellite gravimetry, J. Geod. Geodyn., 32(2), 32-38.

Sanchez-Reales, J., M. Vigo, S.G. Jin, and B. Chao (2012), Global surface geostrophic currents of ocean derived from satellite altimetry and GOCE geoid, Mar. Geod., 35(S1), 175-189, doi: 10.1080/01490419.2012.718696.

Jin, S.G., and X. Zhang (2012), Variations and geophysical excitation of Earth's dynamic oblateness estimated from GPS, OBP, and GRACE, Chin. Sci. Bull., 57(36), 3484-3492, doi: 10.1360/972011-1934.

Jin, S.G., Lijun Zhang, and B. Tapley (2011), The understanding of length-of-day variations from satellite gravity and laser ranging measurements, Geophys. J. Int., 184(2), 651-660, doi: 10.1111/j.1365-246X.2010.04869.x.