Inter-Commission Committee on Theory (ICCT)

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

http://icct.iag-aig.org

Terms of Reference

The Inter-Commission Committee on Theory (ICCT) was formally approved and established after the IUGG XXI Assembly in Sapporo, 2003, to succeed the former IAG Section IV on General Theory and Methodology and, more importantly, to interact actively and directly with other IAG entities, namely commissions, services and the Global Geodetic Observing System (GGOS). In accordance with the IAG by-laws, the first two 4-year periods were reviewed in 2011. IAG approved the continuation of ICCT at the IUGG XXIII Assembly in Melbourne, 2011. At the IUGG XXIV Assembly in Prague, 2015, ICCT became a permanent entity within the IAG structure.

Recognizing that observing systems in all branches of geodesy have advanced to such an extent that geodetic measurements

(i) are now of unprecedented accuracy and quality, can readily cover a region of any scale up to tens of thousands of kilometres, yield non-conventional data types, and can be provided continuously;
and consequently,

(ii) demand advanced mathematical modelling in order to obtain the maximum benefit of such technological advance, ICCT
  (1) strongly encourages frontier mathematical and physical research, directly motivated by geodetic need and practice, as a contribution to science and engineering in general and theoretical foundations of geodesy in particular;
  (2) provides the channel of communication amongst different IAG entities of commissions, services and projects on the ground of theory and methodology, and directly cooperates with and supports these entities in the topical work;
  (3) helps IAG in articulating mathematical and physical challenges of geodesy as a subject of science and in attracting young talents to geodesy. ICCT strives to attract and serve as home to all mathematically motivated and oriented geodesists as well as to applied mathematicians; and
  (4) encourages closer research ties with and gets directly involved in relevant areas of Earth sciences, bearing in mind that geodesy has always been playing an important role in understanding the physics of the Earth.

Objectives

The overall objectives of the ICCT are:

- to act as international focus of theoretical geodesy,
- to encourage and initiate activities to advance geodetic theory in all branches of geodesy,
- to monitor developments in geodetic methodology.

To achieve the objectives, the ICCT interacts and collaborates with the IAG Commissions, GGOS and other IAG related entities (services, projects).

Structure

The structure of Inter-Commission Committees is specified in the IAG by-laws. The ICCT Steering Committee consists of the President, Vice-President, Past-President, representatives from each of the IAG Commissions, GGOS and of two members-at-large.

ICCT activities are undertaken by study groups. By the inter-commission nature of ICCT, these study groups are joint study groups, affiliated to one or more of the Commissions and/or to GGOS.

Program of Activities

The ICCT's program of activities include:

- participation as (co-)conveners of geodesy sessions at major conferences such as IAG, EGU and AGU,
- organization of Hotine-Marussi symposia,
- initiation of summer schools on theoretical geodesy,
- and maintaining a website for dissemination of ICCT related information.

Steering Committee

President	*Pavel Novák* (Czech Rep.)
Vice-President	*Mattia Crespi* (Italy)
Past-President	*Nico Sneeuw* (Germany)
Representatives of IAG entities:	
Commission 1	*Christopher Kotsakis* (Greece)
Commission 2	*Mirko Reguzzoni* (Italy)
Commission 3	*Janusz Bogusz* (Poland)
Commission 4	*Allison Kealy* (Australia)
GGOS	*Michael Schmidt* (Germany)
IGFS	*Riccardo Barzaghi* (Italy)
IERS	*Jürgen Müller* (Germany)
Members at large:	
IAG	*Bofeng Li* (China)
IAG	*Marcelo Santos* (Canada)

Joint Study Groups

The following list names ICCT joint study groups (JSG) for the 2019-2023 period. Their chairs are indicated in boldface. The numbers behind the names denote the affiliation of JSG to the IAG Commissions or GGOS.

JSG T.23 Spherical and spheroidal integral formulas of the potential theory for transforming classical and new gravitational observables
M. Šprlák (Czech Rep.) 2, GGOS

JSG T.24 Integration and co-location of space geodetic observations and parameters
K. Sośnica (Poland) 1, 2, 3, 4, GGOS

JSG T.25 Combining geodetic and geophysical information for probing Earth's inner structure and its dynamics
R. Tenzer (Hong Kong) 2, 3, GGOS

JSG T.26 Geoid/quasi-geoid modelling for realization of the geopotential height datum
J. Huang (Canada) 2, GGOS

JSG T.27 Coupling processes between magnetosphere, thermosphere and ionosphere
A. Calabia (China) 4, GGOS

JSG T.28 Forward gravity field modelling of known mass distributions
D. Tsoulis (Greece) 2, 3, GGOS

JSG T.29 Machine learning in geodesy
B. Soja (Switzerland) 2, 3, 4

JSG T.30 Dynamic modeling of deformation, rotation and gravity field variations
Y. Tanaka (Japan) 2, 3, GGOS

JSG T.31 Multi-GNSS theory and algorithms
A. Khodabandeh (Australia) 1, 4, GGOS

JSG T.32 High-rate GNSS for geoscience and mobility
M. Crespi (Italy) 1, 3, 4, GGOS

JSG T.33 Time series analysis in geodesy and geodynamics
W. Kosek (Poland) 1, 3, 4, GGOS

JSG T.34 High resolution harmonic analysis and synthesis of potential fields
S. Claessens (Australia) 2, GGOS

JSG T.35 Advanced numerical methods in physical geodesy
R. Čunderlík (Slovakia) 2, GGOS

JSG T.36 Dense troposphere and ionosphere sounding
G. Savastano (Luxembourg) 4, GGOS

JSG T.37 Theory and methods related to combination of high-resolution topographic/bathymetric models in geodesy
D. Carrion (Italy) 2, GGOS

JSG T.23: Spherical and spheroidal integral formulas of the potential theory for transforming classical and new gravitational observables

Chair: *M. Šprlák* (Czech Republic)
Affiliation: Commission 2 and GGOS

Introduction

The gravitational field represents one of the principal properties of any planetary body. Physical quantities, e.g., the gravitational potential or its gradients (components of gravitational tensors), describe gravitational effects of any mass body. They help indirectly in sensing inner structures of planets and their (sub-)surface processes. Thus, they represent an indispensable tool for understanding inner structures and processes of planetary bodies and for solving challenging problems in geodesy, geophysics and other planetary sciences.

Various measurement principles have been developed for collecting gravitational data by terrestrial, marine, airborne or satellite sensors. From a theoretical point of view, different parameterizations of the gravitational field have been introduced. To transform observable parameters into sought parameters, various methods have been introduced, e.g., boundary-value problems of the potential theory have been formulated and solved analytically by integral transformations.

Transforms based on solving integral equations of Stokes, Vening-Meinesz and Hotine have traditionally been of significant interest in geodesy as they accommodated gravity field observables in the past. However, new gravitational data have recently become available with the advent of satellite-to-satellite tracking, Doppler tracking, satellite altimetry, satellite gravimetry, satellite gradiometry and chronometry. Moreover, gravitational curvatures have already been measured in laboratory. New observation techniques have stimulated formulations of new boundary-value problems, equally as possible considerations on a tie to partial differential equations of the second order on a two-dimensional manifold. Consequently, the family of surface integral formulas has considerably extended, covering now mutual transformations of gravitational gradients of up to the third order.

In light of numerous efforts in extending the apparatus of integral transforms, many theoretical and numerical issues still remain open. Within this JSG, open theoretical questions related to existing surface integral formulas, such as stochastic modelling, spectral combining of various gradients and assessing numerical accuracy, will be addressed. We also focus on extending the apparatus of spheroidal integral transforms which is particularly important for modelling gravitational fields of oblate or prolate planetary bodies.

Objectives

This JSG plans to:

- Study noise propagation through spherical and spheroidal integral transforms.
- Propose efficient numerical algorithms for precise evaluation of spherical and spheroidal integral transformations.
- Develop mathematical expressions for calculating the distant-zone effects for spherical and spheroidal integral transformations.
- Study mathematical properties of differential operators in spheroidal coordinates which relate various functionals of the gravitational potential.
- Formulate and solve spheroidal gradiometric and spheroidal curvature boundary-value problems.
- Complete the family of spheroidal integral transforms among various types of gravitational gradients and to derive corresponding integral kernel functions.
- Investigate optimal combination techniques of various gravitational gradients for gravitational field modelling at all scales.

Program of Activities

- Presenting findings at international geodetic or geophysical conferences, meetings and workshops.
- Interacting with IAG Commissions and GGOS.
- Monitoring research activities of JSG members and other scientists whose research interests are related to scopes of this JSG.
- Organizing a session at the Hotine-Marussi Symposium 2022.
- Providing a bibliographic list of publications from different branches of the science relevance to scopes of this JSG.

Membership

Michal Šprlák (Czech Republic), chair
Sten Claessens (Australia)
Mehdi Eshagh (Sweden)
Ismael Foroughi (Canada)
Peter Holota (Czech Republic)
Juraj Janák (Slovakia)
Otakar Nesvadba (Czech Republic)
Pavel Novák (Czech Republic)
Vegard Ophaug (Norway)
Martin Pitoňák (Czech Republic)
Michael Sheng (Canada)
Natthachet Tangdamrongsub (USA)
Robert Tenzer (Hong Kong)

JSG T.24: Integration and co-location of space geodetic observations and parameters

Chair: *K. Sośnica* (Poland)
Affiliation: Commissions 1, 2, 3 and 4, GGOS

Introduction

Many geodetic parameters can be retrieved using various techniques of space geodesy. For instance, all satellite techniques are sensitive to a geocenter motion and gravity field variations. However, some techniques are affected more by systematic observation errors than other techniques. Earth's rotation parameters from sub-daily to daily temporal scales can be determined using all techniques of space geodesy with higher or lower accuracy, and with better or worse temporal resolutions. Precise orbits of satellites may be based on a single technique or multiple techniques that shall mitigate system-specific orbital systematic errors.

Recently, a series of satellite missions co-locating different space geodetic techniques has been launched:

- SLR and GNSS: Galileo (all satellites), GLONASS (all satellites), QZSS (all satellites), IRNSS (all satellites), GPS (2 satellites), BeiDou/COMPASS (selected satellites), CHAMP, GRACE-A/B, GOCE, SWARM-A/B/C, ICESat-2, COSMIC-2, Terra-SAR, TanDEM-X, GRACE Follow-On A/B, etc.
- DORIS and SLR: TOPEX/Poseidon, ENVISAT, CRYOSAT-2, SARAL and Jason-1 (after 2009),
- VLBI and SLR: RadioAstron,
- VLBI, SLR, and GNSS: APOD,
- DORIS, GNSS and SLR: Jason-2/3, HY-2A and Sentinel-3A/B,
- SLR, VLBI, GNSS and DORIS: GRASP and E-GRASP (planned missions).

SLR retroreflectors are passive and relatively cheap devices; thus, they are installed on-board many low- and high-orbiting satellites. Many low-orbiting satellites for ocean monitoring are equipped with DORIS and GNSS receivers for precise orbit determination, and with SLR retroreflectors for the orbit validation. DORIS receivers are installed on many satellites which require precise ephemeris and orbit below 2000 km. Missions dedicated to Earth's gravity field recovery are typically equipped with GNSS receivers and SLR retroreflectors. Most of the GNSS satellites are equipped with SLR retroreflectors (except for GPS). VLBI telescopes are typically slow as they are dedicated to tracking extra-galactic quasars. Hence, many VLBI telescopes have problems with tracing fast-moving low-orbiting targets that are planned for co-location on-board satellites. However, first experiments using the APOD satellite with a VLBI transmitter and SLR retroreflector was successfully performed in Australia. Unfortunately, the APOD GPS receiver failed soon after the satellite launch which caused some issues with the accuracy of the determined orbit when the number of SLR observations was insufficient.

Despite many LEO satellites equipped with two or three techniques of space geodesy, the full potential of the co-location on-board LEO has not yet been entirely explored in terms of deriving combined geodetic parameters. SLR observations to LEO are typically used only for validation of GPS-based or DORIS-based orbits. SLR observations to LEO and GNSS do not contribute at all to realization of the International Terrestrial Reference System despite GNSS and LEO satellites contributing to GNSS and DORIS solutions, respectively.

Recently, the International Laser Ranging Service initiated a series of special tracking campaigns dedicated to tracking new LEO and GNSS spacecraft which increased the amount of collected data with a perspective of their full co-location in space. The combination of solutions based on GNSS, SLR, LLR, DORIS and VLBI requires a profound investigation of biases and systematic effects affecting all individual techniques. Neglecting systematic effects may lead to degradation of solutions and to absorption of various systematic effects by global geodetic parameters.

The main goal of this JSG is to investigate methods to combine global geodetic parameters derived from multiple techniques of space geodesy with the major focus on those missions capable of co-locating and integrating different observation techniques. We aim at improving quality and reliability of global geodetic parameters and realization of the terrestrial reference system through integration of different microwave techniques with laser techniques. We will also explore benefits emerging from co-locating geodetic techniques on-board low and high-orbiting satellites. We aim at detailed analyses related to system-specific issues and systematic effects emerging from combining different techniques of space geodesy, and at the assessment of their contributions to combined global geodetic parameters.

Objectives

- Determination of global geodetic parameters using combined space geodetic observations.
- Determination of geocenter motion from: SLR observations to passive and active satellites, DORIS, Galileo, GPS, GLONASS, and BeiDou or possibly also VLBI (using inverse methods).
- Separation of geophysical signals in the geocenter motion from the technique-specific and system-specific errors, employing the co-location in space between SLR and GNSS using Galileo, BeiDou, and GLONASS satellites for deriving common parameters.
- Analysis of potential usability of SLR observations to active LEO satellites together with GNSS and DORIS data for deriving global geodetic parameters.
- Analysis of daily pole coordinates and of length-of-day variations using combined SLR and microwave observations to different GNSS and LEO satellites with DORIS receivers, and the comparison with respect to LLR and VLBI results.
- Determination of sub-daily Earth's rotation parameters from VLBI, GPS, GLONASS, Galileo and SLR observations to LEO and geodetic satellites.
- Precise orbit determination of LEO and GNSS satellites using combined SLR and microwave observations – GNSS and DORIS.
- Estimation of geodetic parameters using GNSS employing time-variable gravity field models derived from SLR, active LEOs and GRACE. Assessment of the vulnerability of satellite orbits to low-degree Earth's gravity field depending on the satellite heights.
- Homogenization of tropospheric delay models for co-located space geodetic stations. Separation of the wet and hydrostatic tropospheric delay; analysis of the

horizontal gradients for optical and microwave techniques.
- Combination of SLR observations to various LEO missions: Sentinel-3A/3B, GRACE, GRACE-FO, GOCE, SWARM-A/B/C, Jason-2/3 to realize the terrestrial reference frames.
- Determination of time-variable low-degree gravity field using SLR observation to passive geodetic satellites and GNSS-based orbits of LEO satellites to fill a gap between GRACE and GRACE-FO missions,
- Estimation of Earth's rotation parameters by combining LLR, SLR and GNSS, and their comparison with VLBI results.

Program of activities

- To launch a questionnaire for the current integration of techniques and finalized co-location in space experiments.
- To open a web page with information concerning the co-location in space, the combination of global geodetic parameters and the exchange of ideas, provision and updating the bibliographic list of references of research results and relevant publications from different combination centers.
- To launch a proposal for two state-of-the-art review papers on co-location on-board LEO and GNSS and combination of global geodetic parameters co-authored by JSG members.
- To organize a session at the Hotine-Marussi Symposium 2022.
- To promote sessions and presentation of the research results at international symposia both related to Earth science, e.g., IAG/IUGG, EGU, AGU, EUREF, IGS and ILRS.

Membership

Krzysztof Sośnica (Poland), chair
Mathis Blossfeld (Germany)
Janina Boisits (Austria)
Grzegorz Bury (Poland)
Florian Dilssner (Germany)
Susanne Glaser (Germany)
Toshimichi Otsubo (Japan)
Erik Schnoemann (Germany)
Dariusz Strugarek (Poland)
Daniela Thaller (Germany)
Tzu-Pang Tseng (Australia)
Radosław Zajdel (Poland)
Julian Zeitlhöfler (Germany)

JSG T.25: Combining geodetic and geophysical information for probing Earth's inner structure and its dynamics

Chair: *R. Tenzer* (Hong Kong)
Affiliation: Commissions 2 and 3, GGOS

Introduction

The seismic tomography is primarily used to provide images of the Earth's inner structure based on the analysis of seismic waves due to earthquakes and (controlled) explosions. This technique involves several different methods for processing P-, S- and surface waves on the principle of solving inverse problems for finding locations of reflection and refraction of wave pathways in order to create topographic models. In this way, 3D models of P- and S-wave seismic velocity anomalies are obtained which can be interpreted as structural, thermal or compositional variations inside the Earth. Focusing on the Earth's density structure, the conversion between seismic velocities and mass densities are adopted to construct regional or global seismic density models of the crust and the mantle. Two major limiting aspects restrict possibilities of recovering Earth's density structure realistically. The first one is practical. Since active seismic experiments are relatively expensive, large parts of the world are not yet covered sufficiently by seismic surveys, most remarkably most of world's oceans as well as remote parts of Antarctica, Greenland, Africa and South America. The other aspect is of a theoretical nature. The determination of mass density from seismic data could be ambiguous while affected by many uncertainties, meaning that the relationship between seismic velocities and mass densities is not unique. Actually, the density structure inside the Earth is controlled by many factors such a thermal state or mineral composition.

Gravity data has been used to interpolate the information about the Earth's density structure (or density interfaces) where seismic data coverage is uneven or sparse. The National Geospatial-Intelligence Agency in conjunction with its partners from around the world has begun to develop a new global gravitational model, EGM2020, which should be released publically in 2020. EGM2020 should significantly improve the accuracy (as well as the actual resolution) of the global Earth's gravity field. This will be achieved by incorporating new data sources and procedures. Updated satellite gravity information from the GOCE and GRACE missions will better support the lower harmonics, globally. Multiple new acquisitions (terrestrial, airborne and shipborne) of gravimetric data over specific regions, will provide improved global coverage and resolution over the land as well as for coastal and some oceanic areas. Ongoing accumulation of satellite altimetry data will contribute to refinement and accuracy improvement of the marine gravity field, most notably in polar and near-coastal regions. A significant improvement is also anticipated over large remote regions in Africa, South America, Greenland and Antarctica. EGM2020 will provide opportunities to improve the current knowledge about the Earth's inner structure and processes particularly in regions with a low seismic data coverage. Gravimetric interpretation of the Earth's inner density structure is, however, a non-unique problem because infinity many density configurations could be attributed just to the one gravity field solution. Moreover, the gravity inversion is (in a broader mathematical context) an ill-posed problem.

To overcome partially theoretical deficiencies and practical restrictions of both, seismic and gravimetric methods for the recovery of the Earth's inner density structure, techniques for a combined or constrained inversions of gravity and seismic data are optimally applied, while incorporating additional geophysical, geological and geodynamic constraints. Many such methods already exist or could be developed and further improved within the framework of scientific activities of members of this (multidisciplinary) study group over the next four years. This is achievable, given their expertise in the field of geodesy, geophysics, mathematics and to some extent also geology.

We expect that our research activities will substantially contribute to the current knowledge of the lithospheric structure, focusing on continental regions of Africa and South America and other continents where seismic data are sparse. Our ongoing research already involves Antarctica and central part of Eurasia. Moreover, a special attention will be given to study the lithospheric structure beneath the Indian Ocean, which is probably the most complex, but the least understood. Despite the lithosphere is the most heterogeneous layer inside the Earth, large lateral structural irregularities are still present even deeper within the mantle below the lithosphere-asthenosphere boundary that are mainly attributed to the mantle convection pattern. The combined gravity and seismic data will be exploited in order to improve existing global or continental-scale mantle density models. A further improvement of the knowledge on the Earth's inner structure is important, among many other subjects, also for a better understanding of the response of the lithosphere to the mantle convection. This involves numerous study topic, including but not limited to the compensation stage of the crust/lithosphere, the lithospheric strength, mechanisms behind the oceanic subduction, the relation between the mantle convection pattern and the global tectonic configuration (and its spatio-temporal variations), the glacial isostatic adjustment, volcanic processes, or geo-hazard. The members of this study group will address some of these aspects within the following overall objectives.

Objectives

The main objectives of the JSG are as follows:

- Improvement of (regional and continental-scale) lithospheric density models based on combining geodetic and geophysical data and additional geological constraining information, focusing mainly on regions with insufficient seismic data coverage. Special emphasis will be given to Africa, Greenland and South America. Studies will involve also Indian and Pacific Oceans.
- Development of a preliminary global density model of the mantle bellow the lithosphere-asthenosphere boundary based on the combined analysis of seismic and gravity data, focusing on the seismic data conversion to mass densities within the gravimetric inversion scheme constrained by geothermal, geochemical, geodynamic and other information.
- Contribution to a better understanding of the interaction between the mantle dynamics and the lithospheric state and structure.

Program of Activities

Presenting research findings at major international geodetic or geophysical conferences, meetings and workshops.
Interacting with related IAG Commissions and GGOS.
Monitoring research activities of the JSG members and of other scientists, whose research interests are relevant to the scopes of the JSG.

Organizing a session at the Hotine-Marussi Symposium 2022.

Providing bibliographic list of publications from different branches of science relevant to JSG scopes.

Membership

Robert Tenzer (Hong Kong), chair
Aleksej Baranov (Russia)
Mohammad Bagherbandi (Sweden)
Carla Braitenberg (Italy)
Wenjin Chen (China)
Róbert Čunderlík (Slovakia)
Franck EK Ghomsi (Cameroon)
Mirko Reguzzoni (Italy)
Lars Sjöberg (Sweden)

JSG T.26: Geoid/quasi-geoid modelling for realization of the geopotential height datum

Chair: *J. Huang* (Canada)
Affiliation: Commission 2 and GGOS

Introduction

The geopotential height datum is realized by a gravimetric geoid/quasi-geoid model. The geoid/quasi-geoid model can now be determined with the accuracy of a few centimeters in a number of regions around the world; it has been adopted in some as a height datum to replace spirit-leveling networks, e.g., in Canada and New Zealand. A great challenge is the 1-2 cm accuracy anywhere to be compatible with the accuracy of ellipsoidal heights measured by the GNSS technology. This requires an adequate theory and its numerical realization, to be of the sub-centimeter accuracy, and the availability of commensurate gravity data and digital elevation models (DEMs).

Geoid/quasi-geoid modelling involves the combination of satellite, airborne and surface gravity data through the remove-compute-restore method, employing various modelling techniques such as the Stokes integration, least-squares collocation, spherical radial base functions or spherical harmonics. Satellite gravity data from recent gravity missions (GRACE and GOCE) enable to model the geoid components with the accuracy of 1-2 cm at the spatial resolution of 100 km. Airborne gravity data are covering more regions with a variety of accuracies and spatial resolutions such as the US GRAV-D project. They often overlap with surface gravity data which are still essential in determining the high-resolution geoid model.

In the meantime, DEMs required for the gravity reduction have achieved higher spatial resolutions with a global coverage. In order to understand how accurately the geoid model can be determined, the 1 cm geoid experiment was carried out in a test region in Colorado, USA by more than ten international teams. The state-of-the-art airborne data was provided for this experiment by US NGS. The test results reveal that differences between geoid models by these teams are at the level of 2-4 cm in terms of the standard deviation with a range of decimeters. Reducing these differences is necessary for realization of geopotential height datums and the International Height Reference System (IHRS). This will require a thorough examination and assessment of both methods and data.

Objectives

The scope of this JSG covers all aspects of geoid/quasi-geoid modelling, in particular focuses on:

- Adoption of physical parameters such as *GM*.
- Determination and adoption of W_0.
- Geo-center convention with respect to the International Terrestrial Reference Frame (ITRF).
- Adoption of a Geodetic Reference System.
- Identification of data requirements and gaps.
- Gravity data gridding methods.
- Downward continuation of high-altitude airborne gravity data.
- Spatial and spectral modelling of topographic effects considering mass density variation.
- Combination of satellite, airborne and surface gravity data.
- Separation between the geoid and quasi-geoid.
- Estimation of data and geoid/quasi-geoid model errors.
- External validation data and methods for the geoid/quasi-geoid model.
- Dynamic geoid/quasi-geoid modelling.
- New geodetic boundary-value problems.

Program of Activities

The JSG will achieve its objectives through:

- Involving and supporting new generation of geoid modelers.
- Organizing splinter meetings in coincidence with major IAG conferences and a series of online workshops.
- Circulating and sharing information, ideas, progress reports, papers and presentations.
- Organizing a session at the Hotine-Marussi Symposium 2022.
- Supporting and cooperating with IAG commissions, services, GGOS and other study and working groups on gravity modelling and height system, in particular GGOS IHRS working group, and International Service for the Geoid (ISG).

Membership

Jianliang Huang (Canada), chair
Jonas Ågren (Sweden)
Riccardo Barzaghi (Italy)
Heiner Denker (Germany)
Bihter Erol (Turkey)
Christian Gerlach (Germany)
Christian Hirt (Germany)
Juraj Janák (Slovakia)
Tao Jiang (China)
Robert W. Kingdon (Canada)
Xiaopeng Li (USA)
Urs Marti (Switzerland)
Ana Cristina de Matos (Brazil)
Pavel Novák (Czech Republic)

Laura Sanchez (Germany)
Matej Varga (Croatia)
Marc Véronneau (Canada)
Yanming Wang (USA)
Xinyu Xu (China)

JSG T.27: Coupling processes between magnetosphere, thermosphere and ionosphere

Chair: *A. Calabia* (China)
Affiliation: Commission 4 and GGOS

Introduction

Consequences of upper-atmosphere conditions on human activity underscore the necessity to better understand and predict effects of the magnetosphere-ionosphere-thermosphere (MIT) processes and of their coupling. This will prevent from their potential detrimental effects on orbiting, aerial and ground-based technologies. For instance, major concerns include the perturbation of electromagnetic signals passing through the ionosphere for an accurate and secure use of global navigation satellite systems (GNSS), and the lack of accurate aerodynamic-drag models required for accurate tracking, decay and re-entry calculations of low Earth orbiters (LEO), including manned and unmanned artificial satellites. In addition, ground power grids and electronics of satellites could be influenced, e.g., by the magnetic field generated by sudden changes in the current system due to solar storms.

Monitoring and predicting Earth's upper atmosphere processes driven by solar activity are highly relevant to science, industry and defense. These communities emphasize the need to increment the research efforts for better understanding of the MIT responses to highly variable solar conditions, as well as detrimental space weather effects on our life and society. On one hand, electron-density variations produce perturbations in speed and direction of various electromagnetic signals propagated through the ionosphere, and reflect as a time-delay in the arrival of the modulated components from which pseudo-range measurements of GNSS are made, and an advance in the phase of signal's carrier waves which affects also carrier-phase measurements. On the other hand, an aerodynamic drag associated with neutral-density fluctuations resulting from upper atmospheric expansion/contraction in response to variable solar and geomagnetic activity increases drag and decelerates LEOs, dwindling the lifespan of space-assets, and making their tracking difficult.

Through interrelations, dependencies and coupling patterns between ionosphere, thermosphere and magnetosphere variability, this JSG aims to improve the understanding of coupled processes in the MIT system, and considerations of the solar contribution. In addition, tides from the lower atmosphere forcing can feed into the electrodynamics; they have a composition effect leading to changes in the MIT system. In this scheme, our tasks are addressed to exploit the knowledge of the tight MIT coupling by investigating multiple types of magnetosphere, ionosphere and thermosphere observations. The final outcome will help to enhance the predictive capability of empirical and physics-based models through interrelations, dependencies and coupled patterns of variability between essential geodetic variables.

Objectives

- Characterize and parameterize global modes of MIT variations associated with diurnal, seasonal and space weather drivers as well as the lower atmosphere forcing.
- Determine and parameterize mechanisms responsible for discrepancies between observables and present models.
- Detect and investigate coupled processes in the MIT system for the deciphering of physical laws and principles such as continuity, energy and momentum equations and solving partial differential equations.

Program of Activities

- Presenting research findings at major international geodetic or geophysical conferences, meetings, and workshops.
- Interacting with related IAG Commissions and GGOS.
- Monitoring research activities of the JSG members and of other scientists, whose research interests are related to the scopes of SG
- Organizing a session at the Hotine-Marussi Symposium 2022.
- Organizing working meetings at international symposia and presentation of research results at appropriate sessions.

Membership

Andres Calabia Aibar (China), chair
Emmanuel Abiodun Ariyibi (Nigeria)
Toyese Tunde Ayorinde (Brazil)
Olawale S. Bolaji (Nigeria)
Oluwaseyi Emmanuel Jimoh (Nigeria)
Gang Lu (USA)
Naomi Maruyama (USA)
Astrid Maute (USA)
Piyush M. Metha (USA)
Charles Owolabi (Nigeria)
Liang Yuan (China)

JSG T.28: Forward gravity field modelling of known mass distributions

Chair: *D. Tsoulis* (Greece)
Affiliation: Commissions 2 and 3, GGOS

Introduction

The geometrical definition of the shape and numerical evaluation of the corresponding gravity signal of any given mass distribution express a central theme in gravity field modelling. Involving different theoretical and computational aspects of the potential field theory and including the element of interpreting the computed signal by comparing it with the observed gravity field, the specific research topic determines a characteristic interface between geodesy and geophysics.

Theoretical and methodological aspects of mass modelling concern a wide range of applications, from computing gravity anomalies and geoid to reducing satellite gradiometry data or solving an extended family of integral equations of the potential theory. Directly linked to real mass density distributions in the Earth's interior, the problem of computing the potential function of given mass density distributions and its spatial derivatives up to higher orders defines the core of forward gravity field modelling, while also constituting an integral part of an inverse modelling flowchart in geophysics.

The availability of an abundance of terrestrial and satellite data of global coverage and increasing spatial resolution provides a challenging framework for revisiting known theoretical aspects and especially investigating computational limits and possibilities of forward gravity modelling induced by known mass distributions. Satellite observations provide global grids of gravity related quantities at satellite altitudes, global crustal databases offer detailed layered information of the shape and consistency of the Earth's crust, while satellite methods produce digital elevation models that represent a continental part of the topographic surface with unprecedented resolution.

The current datasets enable the consideration of several theoretical, methodological and computational aspects of forward gravity field modelling. For instance, dense digital elevation models provide a unique input dataset that challenges the evaluation of precise terrain effects, especially in areas of very steep terrain. At the same time and due to the availability of new data, the complete theoretical framework that evaluates the gravity effect of a given distribution using analytical, numerical or spectral techniques emerges again at the forefront of research, examining both ideal bodies and real distributions. Finally, the existence of detailed information of the structure in the Earth's interior provides an opportunity to revisit synthetic Earth reference models by computing the actual gravity effect induced by these distributions and validate it against the observed gravity signal obtained by the available gravity field models.

Objectives

- Examine new theoretical developments (numerical, analytical or spectral) in expressing the gravity signal of ideal geometric distributions.
- Perform validation studies of precise terrain effects over rugged mountainous topography.
- Compute the gravity effect of structures in the Earth's interior and embed this effort in the frame of a synthetic reference Earth model.

Program of Activities

- Participation in forthcoming IAG conferences with splinter meetings and proposed sessions.
- Preparation of joint publications with JSG members.
- Organization of a session at the Hotine-Marussi Symposium 2022.

Membership

Dimitrios Tsoulis (Greece), chair
Carla Braitenberg (Italy)
Christian Gerlach (Germany)
Ropesh Goyal (India)
Olivier Jamet (France)
Michael Kuhn (Australia)
Pavel Novák (Czech Republic)
Konstantinos Patlakis (Greece)
Daniele Sampietro (Italy)
Matej Varga (Croatia)
Jérôme Verdun (France)

JSG T.29: Machine learning in geodesy

Chair: *B. Soja* (Switzerland)
Affiliation: Commissions 2, 3 and 4

Introduction

Due to the exponential increase in computing power over the last decades, machine learning has grown in importance for several applications. In particular, deep learning, i.e., machine learning based on deep neural networks, typically performed on extensive data sets ("big data"), has become very successful in tackling various challenges, for example, image interpretation, language recognition, autonomous decision making or stock market predictions. Several scientific disciplines have embraced the capability of modern machine learning algorithms, including astronomy and many fields of geosciences.

The field of geodesy has seen a significant increase in observational data in recent years, in particular from Global Navigation Satellite Systems (GNSS) with tens of thousands of high-quality permanent stations, multiple constellations, and increasing data rates. With the upcoming NISAR mission, the InSAR community needs to prepare for handling daily products exceeding 50 GB. In the future, the next-generation Very Long Baseline Interferometry (VLBI) Global Observing System (VGOS) will deliver unprecedented amounts of data compared to legacy VLBI operations. Traditional data processing and analysis techniques that rely largely on human input are not well suited to harvest such rich data sets to their full potential. Still, machine learning techniques are not yet adopted in geodesy.

Machine learning in geodesy has the potential to facilitate the automation of data processing, detection of anomalies in time series and image data, their classification into different categories and prediction of parameters into the future. Machine learning and, in recent years, deep learning methods can successfully model complex spatiotemporal data through the creation of powerful representations at hierarchical levels of abstraction. Furthermore, machine learning techniques provide promising results in addressing the challenges that arise when handling multi-resolution, multi-temporal, multi-sensor, multi-modal data.

The information contained in GNSS station position time series is essential as it can help derive important conclusions related to hydrology, earthquakes, or volcanism using machine learning. Other important applications are tropospheric and ionospheric parameters derived from GNSS where automated detection and prediction could be beneficial for improved severe weather forecasting and space weather monitoring, respectively. InSAR data will benefit in particular from efficient image processing algorithms based on machine learning, facilitating the detection of regions of interest. In several of these cases, the development of scalable deep learning schemes can contribute to more effectively handling and processing of large-scale spatiotemporal data.

Traditional machine learning techniques for geodetic tasks include convolutional neural networks for image data and recurrent neural networks for time series data. Typically, these networks are trained by supervised learning approaches, but certain applications related to autonomous processing will benefit from reinforcement learning.

The field of machine learning has expanded rapidly in recent years and algorithms are constantly evolving. It is the aim of this JSG to identify best practices, methods, and algorithms when applying machine learning to geodetic tasks. In particular, due to the “black box” nature of many machine learning techniques, it is very important to focus on appropriate ways to assess the accuracy and precision of the results, as well as to correctly interpret them.

Objectives

- Identify geodetic applications that could benefit from machine learning techniques, both in terms of which data sets to use and which issues to investigate.
- Create an inventory of suitable machine learning algorithms to address these problems, highlighting their strengths and weaknesses.
- Perform comparisons between machine learning methods and traditional data analysis approaches, e.g., for time series analysis and prediction.
- Focus on error assessment of results produced by machine learning algorithms.
- Identify open problems that come with the automation of data processing and generation of geodetic products, including issues of reliability.
- Develop best practices when applying machine learning methods in geodesy and establishing standardized terminology.

Program of Activities

- Create a web page about machine learning in geodesy to provide information and raise awareness about this topic. The page will include:
  - inventory of algorithms, see above,
  - benchmark datasets to test the performance of these algorithms,
  - comprehensive record of previous activities/ publications related to machine learning in geodesy,
  - description of activities by the JSG members.
- Work toward a state-of-the-art review paper about machine learning in geodesy co-authored by the JSG members.
- Promote sessions and presentation of the research results at international scientific assemblies (IAG/IUGG, EGU, AGU) and technique-specific meetings (IGS, IVS, ...).

Membership

Benedikt Soja (USA), chair
Kyriakos Balidakis (Germany)
Clayton Brengman (USA)
Jingyi Chen (USA)
Maria Kaselimi (Greece)
Ryan McGranaghan (USA)
Randa Natras (Germany)
Simone Scardapane (Italy)

JSG T.30: Dynamic modeling of deformation, rotation and gravity field variations

Chair: *Y. Tanaka* (Japan)
Affiliation: Commissions 2 and 3, GGOS

Introduction

Advancements in the Global Geodetic Observation System (GGOS), and terrestrial, aerial and marine geodetic observations have enabled us to monitor deformation, rotation and gravity field variations of the Earth with the unprecedented accuracy, which are caused by geophysical phenomena having various space-time scales. In addition, recent developments of global networks for solid-Earth observations and technologies for laboratory experiments have allowed us to obtain higher-quality and finer-resolution geophysical data for elasticity, density, viscosity, pressure, electromagnetic and thermal structures, etc., reflecting three dimensional heterogeneities in the internal Earth.

The improved geodetic and geophysical data motivate us to interpret the various phenomena, based on dynamic modelling. Through the modelling, we are able to identify the causes of the detected space-time variations and to deepen the understanding of the phenomena. Furthermore, it would help appeal the usefulness of GGOS.

This JSG consists of scientists working on dynamic modelling using diverse approaches. The targets of the modelling include local, regional and global variations which occur near the surface down to the inner core. To share different perspectives for modelling stimulates the activities of each member and can produce and/or evolve collaborative studies. For which reason, we form a forum within the ICCT.

Objectives

- Development/improvement of forward modelling:
  - Natural phenomena: earthquake, volcano, plate motion, surface fluids, glacial isostatic adjustment (GIA), tides and Earth rotation, etc.
  - Properties of the Earth structure to be modelled: elasticity, viscoelasticity, plasticity, poroelasticity, electromagnetic, thermal and chemical properties, heterogeneities and anisotropies in the Earth structure, etc.
  - Modelling approaches: analytical, semi-analytical and fully numerical methods and associated approximation methods, etc.
  - Comparison between different theories.
  - Opening developed software (if possible).
- Development or improvement of inversion and simulation methods:
  - Integration of diverse data.
  - Effective processing of a large quantity of data.
  - Data assimilation.
  - Application of various theories to real observations for new scientific findings.

Program of Activities

- To launch an e-mail list to share information concerning research results and to interchange ideas for solving related problems.
- To open a web page to share information, such as publication lists and its update.
- To promote international workshops focusing on the above research theme.
- To propel collaborations with closely related joint study groups such as geodetic, seismic and geodynamic constraints on glacial isostatic adjustment, cryospheric deformation and assessing impacts of loading on reference frame realizations.
- To have sessions at international meetings and workshops (EGU, AGU, IAG, Hotine-Marussi Symposium, etc.) as needed.

Membership

Shin-Chan Han (Australia)
Taco Broerse (Netherlands)
José Fernández (Spain)
Guangyu Fu (China)
Hom Nath Gharti (USA)
Pablo J. González (Spain)
Cheinway Hwang (Taiwan)
Volker Klemann (Germany)
Zdeněk Martinec (Ireland)
Daniel Melini (Italy)
Anthony Mémin (France)
Craig Miller (New Zealand)
Jun'ichi Okuno (Japan)
Riccardo Riva (Netherlands)
Jeanne Sauber (USA)
Giorgio Spada (Italy)
Yoshiyuki Tanaka (Japan), chair
Peter Vajda (Slovak Republic)
Wouter van der Wal (Netherlands)

JSG T.31: Multi-GNSS theory and algorithms

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

Introduction

The family of modernized and recently-developed global and regional navigation satellite systems is being further extended by plentiful Low Earth Orbit (LEO) navigation satellites that are almost 20 times closer to Earth as compared to current GNSS satellites. This namely means that navigation sensory data with much stronger signal power will be abundantly available, being in particular attractive in GNSS-challenged environments. Next to the development of new navigation signal transmitters, a rapid growth in the number of mass-market GNSS and software-defined receivers would at the same time demand efficient ways of data processing in terms of computational power and capacity.

Such a proliferation of multi-system and multi-frequency measurements, that are transmitted and received by mixed-type sensing modes, raises the need for a thorough research into the future of next-generation navigation satellite systems, thereby appealing rigorous theoretical frameworks, models and algorithms that enable such GNSS-LEO integration to serve as a high-accuracy and high-integrity tool for Earth-, atmospheric- and space-sciences.

Objectives

The main objectives of this JSG are to:

- Identify and investigate challenges that are posed by the integration of multi-GNSS and LEO observations.
- Develop and study proper theory for GNSS integrity and quality control.
- Conduct an in-depth analysis of the mass-market GNSS sensory data such as those of smart-phones.
- Improve computational efficiency of GNSS parameter estimation and testing in the presence of a huge number of GNSS sensing nodes.
- Investigate the problem of high-dimensional integer ambiguity resolution and validation in a multi-system, multi-frequency landscape.
- Articulate theoretical developments and findings through the journals and conference proceedings.

Program of Activities

While the investigation will strongly be based on the theoretical aspects of the GNSS-LEO observation modelling and challenges, they will be also accompanied by numerical studies of both the simulated and real-world data. Given the expertise of each member, the underlying studies will be conducted on both individual and collaborative bases. The output of the group study is to provide the geodesy and GNSS communities with well-documented models and algorithmic methods through the journals and conference proceedings.

Membership

Amir Khodabandeh (Australia), chair
Ali Reza Amiri-Simkooei (Iran)
Gabriele Giorgi (Germany)
Bofeng Li (China)
Robert Odolinski (New Zealand)
Jacek Paziewski (Poland)
Dimitrios Psychas (The Netherlands)
Jean-Marie Sleewagen (Belgium)
Peter J.G. Teunissen (Australia)
Baocheng Zhang (China)

JSG T.32: High-rate GNSS for geoscience and mobility

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

Introduction

Global Navigation Satellite Systems (GNSS) have become for a long time an indispensable tool to get accurate and reliable information about positioning and timing; in addition, GNSS are able to provide information related to physical properties of media passed through by GNSS signals. Therefore, GNSS play a central role both in geodesy and geomatics and in several branches of geophysics, representing a cornerstone for the observation and monitoring of our planet.

So, it is not surprising that, from the very beginning of the GNSS era, the goal was pursued to widen as much as possible the range in space (from local to global) and time (from short to long term) of the observed phenomena, in order to cover the largest possible field of applications, both in science and in engineering. Two additional primary goals were, obviously, to get this information with the highest accuracy and in the shortest time.

The advances in technology and the deployment of new constellations, after GPS (in the next few years the European Galileo, the Chinese Beidou and the Japanese QZSS will be completed) remarkably contributed to transform this *three-goals dream* in reality, but still remain significant challenges when very fast phenomena have to be observed, mainly if real-time results are looked for.

Actually, for almost 15 years, starting from the noble birth in seismology, and the very first experiences in structural monitoring, high-rate GNSS has demonstrated its usefulness and power in providing precise positioning information in fast time-varying environments. At the beginning, high-rate observations were mostly limited at 1 Hz, but the technology development provided GNSS equipment (in some cases even at low-cost) able to collect measurements at much higher rates, up to 100 Hz, therefore opening new possibilities, and meanwhile new challenges and problems.

So, it is necessary to think about how to optimally process this potential huge heap of data, in order to supply information of high value for a large (and increasing) variety of applications, some of them listed hereafter without the claim to be exhaustive: better understanding of the geophysical/geodynamical processes mechanics; monitoring of ground shaking and displacement during earthquakes, also for contribution to tsunami early warning; tracking the fast variations of the ionosphere; real-time controlling landslides and the safety of structures; providing detailed trajectories and kinematic parameters (not only position, but also velocity and acceleration) of high dynamic platforms such as airborne sensors, high-speed terrestrial vehicles and even athlete and sport vehicles monitoring.

Further, due to the contemporary technological development of other sensors (hereafter referred as ancillary sensors) related to positioning and kinematics able to collect high-rate data (among which MEMS accelerometers and gyros play a central role, also for their low-cost), the feasibility of a unique device for high-rate observations embedding GNSS receiver and MEMS sensors is real, and it opens, again, new opportunities and problems, first of all related to sensors integration.

In this respect, Android based mass-market devices (smartphones and tablets) are nowadays able to provide 1 Hz raw GNSS measurements (with a growing number of models able to provide multi-constellation and multi-frequency code and phase observations) in addition to the above-mentioned ancillary sensors measurements.

All in all, it is clear that high-rate GNSS (and ancillary sensors) observations represent a great resource for future investigations in Earth sciences and applications in engineering, meanwhile stimulating a due attention from the methodological point of view in order to exploit their full potential and extract the best information. This is the why it is worth to open a focus on high-rate (and, if possible, real-time) GNSS within ICCT.

Objectives

- To realize the inventories of:
  - the available and applied methodologies for high-rate GNSS, in order to highlight their pros and cons and the open problems
  - the present and wished applications of high-rate GNSS for science and engineering, with a special concern to the estimated quantities (geodetic, kinematic, physical), in order to focus on related problems (still open and possibly new) and draw future challenges
  - the technology (hw, both for GNSS and ancillary sensors, and sw, possibly FOSS), pointing out what is ready and what is coming, with a special concern for the supplied observations and for their functional and stochastic modeling with the by-product of establishing a standardized terminology.
- To address known (mostly cross-linked) problems related to high-rate GNSS as (not an exhaustive list): revision and refinement of functional and stochastic models; evaluation and impact of observations time-correlation; impact of multipath and constellation change; outlier detection and removal; issues about GNSS constellations interoperability; ancillary sensors evaluation, cross-calibration and integration.
- To address new problems and future challenges which arise from inventories.
- To investigate about the interaction with present real-time global (IGS-RT, EUREF-IP, etc.) and regional/local positioning services: how can these services support high-rate GNSS observations and, on reverse, how can they benefit of high-rate GNSS observations

Program of Activities

- To launch a questionnaire for the above mentioned inventory of methodologies, applications and technologies.
- To open a web page with information concerning high-rate GNSS and its wide applications in science and engineering, with special emphasis on exchange of ideas, raw relevant datasets, provision and updating bibliographic list of references of research results and relevant publications from different disciplines.
- To launch the proposal for two (one science and the other engineering oriented) state-of-the-art review papers in high-rate GNSS co-authored by JSG members.
- To promote sessions and presentation of research results at international symposia both related to Earth science (IAG/IUGG, EGU, AGU, EUREF, IGS), engineering (workshops and congresses in structural, geotechnical, mechanical, transport and automotive engineering), and life sciences (sports and health care).

Membership

Mattia Crespi (Italy), chair
Elisa Benedetti (United Kingdom)
Mara Branzanti (Switzerland)
Liang Chen (China)
Gabriele Colosimo (Switzerland)
Elisabetta D'Anastasio (New Zealand)
Roberto Devoti (Italy)
Rui Fernandes (Portugal)
Marco Fortunato (Italy)
Athanassios Ganas (Greece)
Pan Li (Germany)
Alain Geiger (Switzerland)
Jianghui Geng (China)
Dara Goldberg (USA)
Kathleen Hodgkinson (USA)
Shuanggen Jin (China)
Iwona Kudlacik (Poland)
Jan Kaplon (Poland)
Augusto Mazzoni (Italy)
Joao Francisco Galera Monico (Brazil)
Héctor Mora Páez (Colombia)
Michela Ravanelli (Italy)
Giorgio Savastano (Luxembourg)
Sebastian Riquelme (Chile)
Peiliang Xu (Japan)

JSG T.33: Time series in geodesy and geodynamics

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

Introduction

Observations of the space geodesy techniques enable measuring Earth's gravity variations caused by mass displacement, the change in the Earth's shape, and the change in the Earth's rotation. The Earth's rotation represented by the Earth Orientation Parameters (EOP) should be observed with possibly the smallest latency to provide real-time transformation between the International Terrestrial and Celestial Reference Frames (ITRF and ICRF). Observed by GRACE missions, redistribution of mass within the fluid layers relative to the solid Earth induces exchange of angular momentum between these layers and solid Earth, changes in the Earth's inertia tensor.

Redistribution of masses induce temporal variations of Earth's gravity field where 1 degree spherical harmonics correspond to the Earth's centre of mass variations (long term mean of them determines the ITRF origin) and 2 degree spherical harmonics correspond to Earth rotation changes. Satellite altimetry enables observation of changes in geometry of sea level and space geodesy techniques enable observations of changes in geometry of the Earth's crust by monitoring horizontal and vertical deformations of site positions. Sea surface height varies due to thermal expansion of sea water and changes in ocean water mass arising from melting polar ice cap, mountain glacier ice, as well as due to groundwater storage. The site positions which are determined together with satellite orbit parameters (in the case of SLR, GNSS and DORIS) or radio source coordinates (in the case of VLBI) and Earth orientation parameters (x, y pole coordinates, UT1-UTC/LOD and precession-nutation corrections dX, dY) are then used to build the global ITRF which changes due to e.g. plate tectonics, postglacial rebound, atmospheric, hydrology and ocean loading and earthquakes. In these three components of geodesy which should be integrated into one unique physical and mathematical model there are changes that are described by spatial and temporal geodetic time series.

Different time series analysis methods have been applied to analyze all elements of the Earth's system for better understanding the mutual relationship between them. The nature of considered signals in the geodetic time series is mostly wideband, irregular and non-stationary. Thus, it is recommended to apply spectra-temporal analyzes methods to analyze and compare these series to explain the mutual interaction between them in different time and different frequency bands. The main problems to deal with is to estimate the deterministic (including trend and periodic variations) and stochastic (non-periodic variations and random changes described by different noise characters) components in these geodetic time series as well as to apply the appropriate methods of spectra-temporal comparison of these series.

The multiple methods of time series analysis may be encouraged to be applied to the preprocessing of raw data from various geodetic measurements in order to promote the quality level of enhancement of signals existing in these data. The topic on the improvement of the edge effects in time series analysis should be also considered, since they may affect the reliability of long-range tendency (trends) estimated from data series as well as the real-time data processing and prediction. For coping with small geodetic samples one can apply simulation-based methods and if the data are sparse, Monte-Carlo simulation or bootstrap technique may be useful.

Measurements by space geodetic techniques provide an important contribution to the understanding of climate change. The analysis of Earth rotation and geophysical time series as well as global sea level variations shows that there is a mutual relationship between them for oscillations with periods from a few days to decades. The thermal annual cycle caused by the Earth's orbital motion modified by variable solar activity induces seasonal variations the Earth's fluid layers, thus in the Earth rotation, sea level variations as well as in the changes of the Earth's gravity field and centre of mass. The interrelationships between the geodetic time series and changes of global troposphere temperature show that they provide very important information about the Earth's climate change (for example global sea level increases faster during El Nino events associated with the increase of global temperature and in this time the increase of length of day can be also noticed). Thus, the spectra-temporal analysis and comparison of geodetic time series should also include time series associated with solar activity.

Objectives

- Study of the nature of geodetic time series to choose optimum time series analysis methods for filtering, spectral analysis, time frequency analysis and prediction.
- Study of Earth's geometry, rotation and gravity field variations and their geophysical causes in different frequency bands.
- Evaluation of appropriate covariance matrices for the time series by applying the law of error propagation to the original measurements, including weighting schemes, regularization, etc.
- Determination of the statistical significance levels of the results obtained by different time series analysis methods and algorithms applied to geodetic time series.
- Comparison of different time series analysis methods in order to point out their advantages and disadvantages.
- Application and development of time frequency analysis methods to detect the relationship between geodetic time series and time series associated with the solar activity in order to solve the problems related to the climate change.
- Recommendations of different time series analysis methods for solving problems concerning specific geodetic time series.
- Detection of reliable station velocities and their uncertainties with taking into account their non-linear motion and environmental loadings and identification of site clusters with similar velocities
- Deterministic and stochastic modelling and prediction of troposphere and ionosphere parameters for real time precise GNSS positioning.
- Better Earth Orientation Parameters short-term prediction using the extrapolation models of the fluid excitation functions.

Program of Activities

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

Membership

Wieslaw Kosek (Poland), chair
Orhan Akyilmaz (Turkey)
Johannes Boehm (Austria)
Xavier Collilieux (France)
Olivier de Viron (France)
Laura Fernandez (Argentina)
Richard Gross (USA)
Mahmut O. Karslioglu (Turkey)
Anna Kłos (Poland)
Hans Neuner (Germany)
Tomasz Niedzielski (Poland)
Sergei Petrov (Russia)
Waldemar Popiński (Poland)
Michael Schmidt (Germany)
Michel Van Camp (Belgium)
Jan Vondrák (Czech Republic)
Dawei Zheng (China)
Yonghong Zhou (China)

JSG T.34: High-resolution harmonic series of gravitational and topographic potential fields

Chair: *S. Claessens* (Australia)
Affiliation: Commission 2 and GGOS

Introduction

The resolution of models of the gravitational and topographic potential fields of the Earth and other celestial bodies in the Solar System has increased steadily over the last few decades. These models are most commonly represented as a spherical, spheroidal or ellipsoidal harmonic series. Harmonic series are used in many other areas of science such as geomagnetism, particle physics, planetary geophysics, biochemistry and computer graphics, but geodesists are at the forefront of research into high-resolution harmonic series.

In recent years, there has been increased interest and activity in high-resolution harmonic modelling (to spherical harmonic degree and order (d/o) 2190 and beyond). In 2019, the first model of the Earth's gravitational potential in excess of d/o 2190 was listed by the International Centre for Global Earth Models (ICGEM). All high-resolution models of gravitational potential fields rely on forward modelling of topography to augment other sources of information. Harmonic models of solely the topographic potential are also becoming more common. Models of the Earth's topographic potential up to spherical harmonic d/o 21,600 have been developed, and ICGEM has listed topographic gravity field models since 2014.

The development of high-resolution harmonic models has posed and continues to pose both theoretical and practical challenges for the geodetic community.

One challenge is the combination of methods for ultra-high d/o harmonic analysis (the forward harmonic transform). Least-squares-type solutions with full normal equations are popular, but computationally prohibitive at ultra-high d/o. Alternatives are the use of block-diagonal techniques or numerical quadrature techniques. Optimal combination and comparison of the different techniques, including studying the influence of aliasing, requires further study.

A related issue is the development of methods for the optimal combination of data sources in the computation of high-degree harmonic models of the gravitational potential. Methods used for low-degree models cannot always suitably be applied at higher resolution.

Another challenge is dealing with ellipsoidal instead of spherical geometry. Much theory has been developed and applied in terms of spherical harmonics, but the limitations of the spherical harmonic series for use on or near the Earth's surface have become apparent as the maximum d/o of the harmonic series has increased. The application of spheroidal or ellipsoidal harmonic series has become more widespread, but needs further theoretical development.

A specific example is spectral forward modelling of the topographic potential field in the ellipsoidal domain. Various methods have been proposed, but these are yet to be compared from both a theoretical and numerical standpoint. There are also still open questions about the divergence effect and the amplification of the omission error in spherical and spheroidal harmonic series inside the Brillouin surface.

A final challenge are numerical instabilities, underflow/overflow and computational efficiency problems in the forward and reverse harmonic transforms. Much progress has been made on this issue in recent years, but further improvements may still be achieved.

Objectives

The objectives of this JSG are to:

- Develop and compare combined full least-squares, block-diagonal least-squares and quadrature approaches to very high-degree and order spherical, spheroidal and ellipsoidal harmonic analysis.
- Develop and compare methods to compute high-resolution harmonic potential models using ellipsoidal geometry, either in terms of spherical, spheroidal or ellipsoidal harmonic series.
- Study the divergence effect of ultra-high degree spherical, spheroidal and ellipsoidal harmonic series inside the Brillouin sphere, spheroid and/or ellipsoid.
- Study efficient methods for ultra-high degree and order harmonic analysis (the forward harmonic transform) for a variety of data types and boundary surfaces, as well as harmonic synthesis (the reverse harmonic transform) of various quantities.

Program of Activities

To facilitate achievement of these objectives, the group will provide a platform for increased collaboration between group members, encouraging exchange of ideas and research results. Working meetings of group members will be organized at major international conferences.

Membership

Sten Claessens (Australia), chair
Hussein Abd-Elmotaal (Egypt)
Blažej Bucha (Slovakia)
Christoph Förste (Germany)
Toshio Fukushima (Japan)
Ropesh Goyal (India)
Christian Hirt (Germany)
Norbert Kühtreiber (Austria)
Kurt Seitz (Germany)
Elmas Sinem Ince (Germany)
Michal Šprlák (Czech Republic)
Philipp Zingerle (Germany)

JSG T.35: Advanced numerical methods in physical geodesy

Chair: *R. Čunderlík* (Slovakia)
Affiliation: Commission 2 and GGOS

Introduction

Advanced numerical methods and high performance computing (HPC) facilities provide new opportunities in many applications in geodesy. The goal of this JSG is to apply such numerical methods to solve various problems of physical geodesy, mainly gravity field modelling, processing satellite observations, nonlinear data filtering or others. It focuses on a further development of approaches based on discretization numerical methods like the finite element method (FEM), finite volume method (FVM) and boundary element method (BEM) or the meshless collocation techniques like the method of fundamental solutions (MFS) or singular boundary method (SOR). Such approaches allow gravity field modelling in spatial domain while solving the geodetic boundary-value problems (GBVPs) directly on the discretized Earth's surface. Their parallel implementations and large-scale parallel computations on clusters with distributed memory allow high-resolution numerical modelling.

The JSG is also open to new innovative approaches based for example on the computational fluid dynamics (CFD) techniques, spectral FEM, advection-diffusion equations, or similar approaches of scientific computing. It is also open for researchers dealing with classical approaches of gravity field modelling like the spherical or ellipsoidal harmonics that are using HPC facilities to speed up their processing of enormous amount of input data. This includes large-scale parallel computations on massively parallel architectures as well as heterogeneous parallel computations using graphics processing units (GPUs).

Objectives

The objectives of this JSG are to:

- Design the FEM, BEM and FVM numerical models for solving GBVPs with the oblique derivative boundary conditions.
- Develop algorithms for a discretization of the Earth's surface based on adaptive refinement procedures (the BEM approach).
- Develop algorithms for an optimal construction of 3D unstructured meshes above the Earth's topography (the FVM or FEM approaches).
- Design numerical models based on MFS or SBM for processing the GOCE gravity gradients in spatial domain.
- Design algorithms for 1D along track filtering of satellite data, e.g., from the GOCE satellite mission.
- Develop numerical methods for nonlinear diffusion filtering of data on the Earth's surface based on solutions of the nonlinear heat equations.
- Investigate innovative approaches based on the computational fluid dynamics (CFD) techniques, spectral FEM or advection-diffusion equations.
- Apply parallel algorithms using MPI procedures.
- Apply large-scale parallel computations on clusters with distributed memory.

Program of Activities

- Active participation in major geodetic conferences.
- Working meetings at international symposia.
- Organization of a conference session.

Membership

Róbert Čunderlík (Slovakia), chair
Petr Holota (Czech Republic)
Michal Kollár (Slovakia)
Marek Macák (Slovakia)
Matej Medľa (Austria)
Karol Mikula (Slovakia)
Zuzana Minarechová (Slovakia)
Otakar Nesvadba (Czech Republic)
Yoshiyuki Tanaka (Japan)
Robert Tenzer (Hong Kong)
Zhi Yin (Germany)

JSG T.36: Dense troposphere and ionosphere sounding

Chair: *G. Savastano* (Luxembourg)
Affiliation: Commission 4 and GGOS

Introduction

Global Navigation Satellite Systems Radio Occultation (GNSS-RO) have become an important technique to globally sound the Earth's atmosphere from space. This technique overcomes some of the main limitations of ground-based remote sensing instruments, increasing the amount of tropospheric and ionospheric data measured over the oceans and under sampled regions.

Up until few years ago, GNSS-RO observations were mainly supported by expensive satellite missions (e.g. COSMIC-1), which implies also considerably high operational costs. A great opportunity was brought in the field by nanosatellites, which are a satellite of low mass and size, usually under 500 kg. These satellites can significantly reduce the large economic cost of launch vehicles and the costs associated with construction.

In recent years, commercial RO providers (e.g., Spire Global) shifted the paradigm and started operationally producing GNSS-RO data from CubeSats in Low Earth Orbit (LEO). This data was demonstrated to be comparable in quality to larger satellite constellations (e.g., COSMIC-1), but with a denser spatial and temporal coverage. The new paradigm proposed by these commercial companies is that nanosatellites, especially in large numbers, may be more beneficial than using fewer, larger satellites in tasks such as gathering scientific data.

Independent assessments of these commercial data quality were carried out by JPL, UKMO, ESA, NOAA, and NRL, which convinced the international RO community that commercial data are ready to be assimilated by NWP centres and used by scientists to investigate different research topics.

Often, these nanosatellites carry different scientific payloads collecting a large amount of different data (e.g., GNSS-POD solutions, GNSS top ionosphere TEC observations), that could be exploited for several scientific investigations. Furthermore, contemporary technological advances of other low-cost sensors (e.g., in-situ atmospheric sensors, MEMS accelerometers and gyros) opens new opportunity and problems, first of all related to data fusion, validation and sensor integration.

Spire will share data samples (e.g., podGps, atmPhs, podTec, atmPrf) within the members of the study group, in order to promote the development of new algorithms and methodologies for remote sensing of the Earth.

It is clear that this unprecedented dense coverage of troposphere and ionosphere sounding enabled by commercial GNSS-RO CubeSats and dense network of ground-based GNSS receivers represents a great opportunity for future investigations in Earth sciences. This brings the attention to the methodological point of view in order to exploit their full potential and extract the best information. This is the reason why it is worth opening a focus on dense troposphere and ionosphere sounding using GNSS-RO and ground-based GNSS techniques within ICCT.

Objectives

- To realize inventories of:
  - commercial and publicly available GNSS-RO and ground-based GNSS observations, with a distinction between troposphere and ionosphere observations, and a classification based on the different acquisition parameters (e.g., sampling rate, vertical or temporal resolution, altitude range of acquisition, tracking mode),
  - present and wished applications of dense troposphere and ionosphere sounding for science and engineering, with a special concern to the estimated physical quantities (e.g., temperature, pressure and TEC), in order to focus on related problems (still open and possibly new) and draw future challenges.
- To address known problems related to dense troposphere and ionosphere sounding using GNSS-RO observations as (not an exhaustive list): atmospheric anomalies detection, localization and classification; revision and refinement of inversion techniques; temporal variability of receivers DCBs and evaluation of their impact in the calibrated process; data quality assessment and validation; outlier detection and removal; in-situ sensors evaluation, cross-calibration and integration.
- To describe the different analytical and physical implication of combining observations collected with different observational geometries, such as: ground-based receivers tracking signals transmitted by GNSS satellites in MEO and GEO orbits; space-based receivers tracking GNSS signals at different elevation angles (from positive to negative and vice versa). Furthermore, investigate the different ways of combining together these remote sensing observations to retrieve fundamental atmospheric parameters, and disentangle the spatial and temporal variability of the atmosphere.

Program of Activities

- To organize a session at the forthcoming Hotine-Marussi symposium 2022.
- To convene at international conferences such as IAG/IUGG, EGU, AGU.

Membership

Giorgio Savastano (Luxembourg), chair
Matthew Angling (UK)
Elvira Astafyeva (France)
Riccardo Biondi (Italy)
Mattia Crespi (Italy)
Kosuke Heki (Japan)
Addisu Hunegnaw (Luxembourg)
Alessandra Mascitelli (Italy)
Giovanni Occhipinti (France)
Michela Ravanelli (Italy)
Eugenio Realini (Italy)
Lucie Rolland (France)
Felix Norman Teferle (Luxembourg)
Jens Wickert (Germany)

JSG T.37: Theory and methods related to combination of high-resolution topographic/ bathymetric models in geodesy

Chair: **D. Carrion** (Italy)
Affiliation: Commission 2 and GGOS

Introduction

Topographic and bathymetric models constitute a fundamental input for geodetic computations, e.g. for the evaluation of terrain effects for local and global geoid estimation. In this regard, the Shuttle Radar Topography Mission (SRTM) provided a very significant contribution to the knowledge of terrain heights over land. Great advantages provided by SRTM are the homogeneity of its spatial resolution and its (almost) global coverage. In addition, the spatial resolution of SRTM is adequate for the majority of geodetic applications.

The situation is quite different concerning currently available bathymetric models: in this case, the resolution is not homogeneous around the Earth and the level of accuracy can vary considerably from one area to another. In addition, when considering the transition between land surface and sea bottom, the combination of topographic and bathymetric models can be challenging, due to the limitations linked to resolution and accuracy of data and to local datum inconsistencies, which could be neglected in global models.

Different combined products are available at global level, such as SRTM+, however the poor knowledge of the sea bottom or datum issues, may lead to problems in geodetic computations and should be further investigated. Apart from geodetic applications, the precise knowledge of the land-sea transition is crucial for modelling of other environmental processes in the coastal zone, such as the impact of sea level change and extreme sea level events such as storm surges and tsunamis.

This JSG aims at studying the available topographic and bathymetric models and at exploring their limitations, in particular concerning the transition along the coasts.

Objectives

- Highlight the issues of the topography/sea bottom transition through literature examples.
- Analyse available data on global and local topographic and bathymetric models, highlighting the issues, based also on personal research experience.
- Verify the quality of the transition through test cases.
- Suggest best practices for combination of models.
- Identify the need for data acquisition in specific areas.

Program of Activities

- Explore available data and literature research.
- Propose review papers concerning the state of the art knowledge on the combination of topographic and bathymetric models.
- Cooperate with IAG Commissions and other JSGs.
- Organize meetings, workshops and sessions at selected conferences, e.g. during Hotine-Marussi 2022.

Membership

Daniela Carrion (Italy), chair
Riccardo Barzaghi (Italy)
Mattia Crespi (Italy)
Vassilios Grigoriadis (Greece)
Karsten Jacobsen (Germany)
Kevin Kelly (US)
Michael Kuhn (Australia)
Cornelis Slobbe (Netherlands)
Roberto Teixeira Luz (Brazil)
Ana Cristina de Matos (Brazil)
Dan Palcu (Brazil)
Ionut Sandric (Romania)
Georgios S. Vergos (Greece)