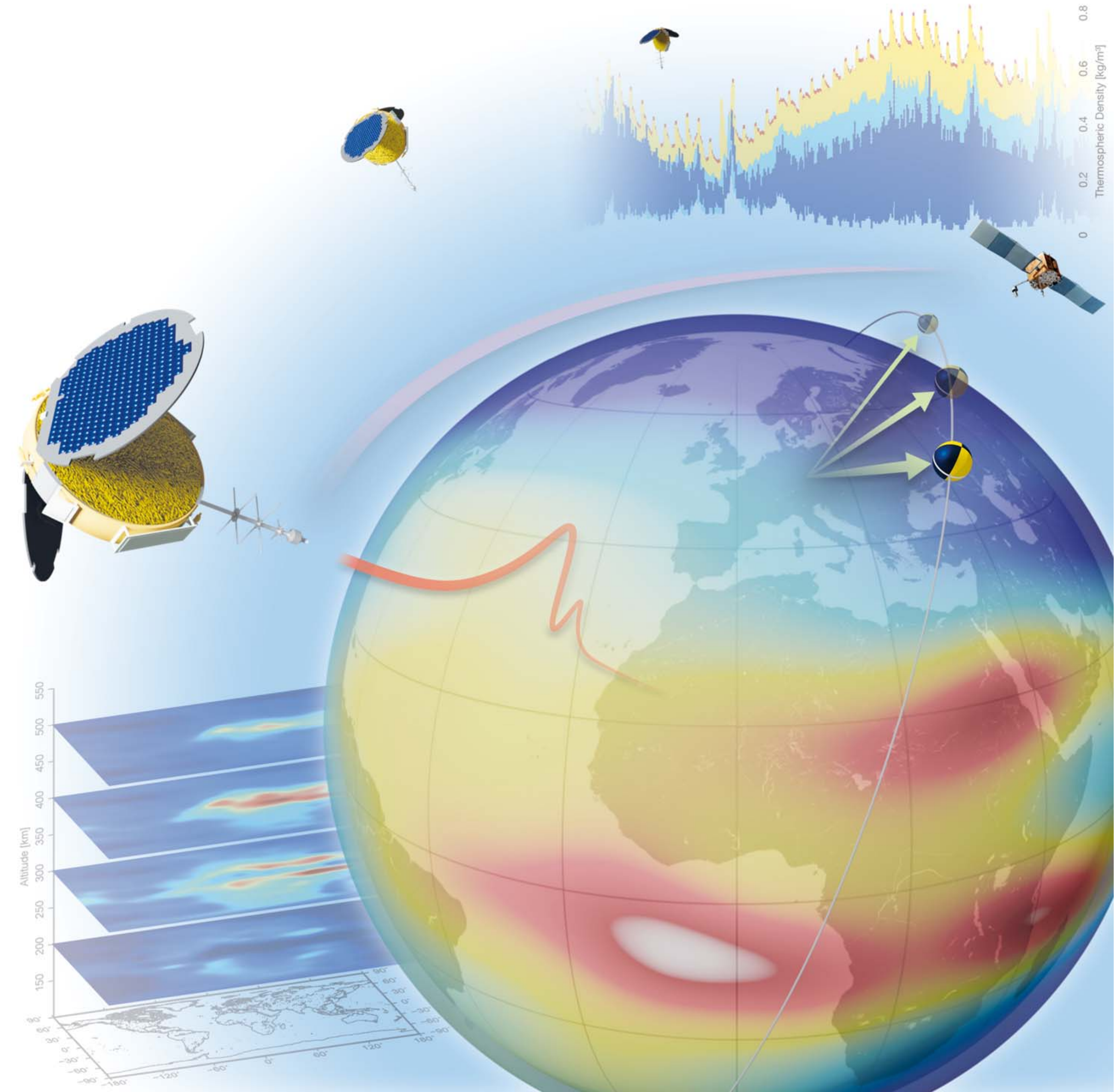
Deutsches Geodätisches Forschungsinstitut
Ingenieurfakultät Bau Geo Umwelt
Technische Universität München

Annual Report 2017

Deutsches Geodätisches Forschungsinstitut der Technischen Universität München (DGFI-TUM)



Front cover:

The picture shows a constellation of different satellites that are used by DGFI-TUM to derive information about the state and the temporal variations of the Earth's ionosphere and thermosphere. The satellite on the left side (shown in three different positions as it travels along its orbit) belongs to the Formosat-3/COSMIC satellite system. Occultation measurements between these satellites and GNSS (on the right) allow to derive electron density profiles (orange-colored profile) vertically through the ionosphere. Combining occultations with measurements of other space-geodetic techniques such as GNSS, satellite altimetry and DORIS yields a 4D global electron density model (visualized as a layer model in the bottom left part of the picture). The vertical integration of the electron density results in the so-called vertical total electron content (VTEC). Its global distribution is plotted on a sphere enveloping the globe. The equatorial anomaly as the main feature of the VTEC (red structure) is clearly visible.

The panel in the top right corner shows the neutral density computed from different empirical thermosphere models over time. It determines the thermospheric drag as the main disturbing factor within the precise orbit determination (POD) of low-Earth-orbiting (LEO) satellites. Thus, a POD of LEO satellites by Satellite Laser Ranging (indicated in the right part of the picture) provides information of the thermosphere. Further details, including the coupling processes between electron and neutral density can be found in Section 3.1 of this report.

Since 2017, the DGFI-TUM leads the newly implemented *Focus Area on Geodetic Space Weather Research* of the Global Geodetic Observing System (GGOS) under the umbrella of the International Association of Geodesy (IAG).

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Preface

The Institute

The Deutsches Geodätisches Forschungsinstitut (DGFI-TUM) is a research institute of the Technical University of Munich (TUM). It is part of the Chair of Geodetic Geodynamics within TUM's Faculty of Civil, Geo and Environmental Engineering (BGU).

The DGFI-TUM performs basic research in the field of Space Geodesy with the ambition to provide a comprehensive and long-term valid metric of the Earth system for science and practice at highest precision and consistency. In strong international and interdisciplinary collaboration, DGFI-TUM processes, analyses and combines observations from all relevant space geodetic observing systems and complementary data sources at the highest level of scientific knowledge. In particular, the institute possesses unique competence in determining the Earth's time-variable surface geometry (solid Earth and water surfaces) and atmospheric disturbances.

The precise determination of the Earth's geometrical shape and its temporal changes has always been a central aspect of the institute's research. For the solid Earth, this involves in particular the realization of global and regional horizontal and vertical terrestrial reference systems and of the celestial reference system. With respect to water surfaces, the institute has a key focus in the precise determination of the changing sea level and water stages of lakes, rivers and wetlands using satellite altimetry.

DGFI-TUM's strategic focus is reflected by its organization into the two research areas *Reference Systems* and *Satellite Altimetry* (Fig. 1). The two research areas are complemented by three overarching research topics that cover the investigation of the state and dynamics of the atmosphere (with a strong focus on ionospheric disturbances), the determination of high resolution regional gravity fields, and the establishment of unique standards and conventions for geodetic data analysis worldwide.

The institute contributes to the scientific data processing of the Geodetic Observatories Wettzell (Germany) and AGGO (Argentina) in the frame of the Research Group Satellite Geodesy (FGS) and operates several worldwide distributed GNSS stations. DGFI-TUM collaborates at key positions in international scientific organizations, in particular within the framework of the International Union of Geodesy and Geophysics (IUGG), the International Association of Geodesy (IAG) and the International Astronomical Union (IAU), and thus contributes to shaping the future direction of international geodetic research.

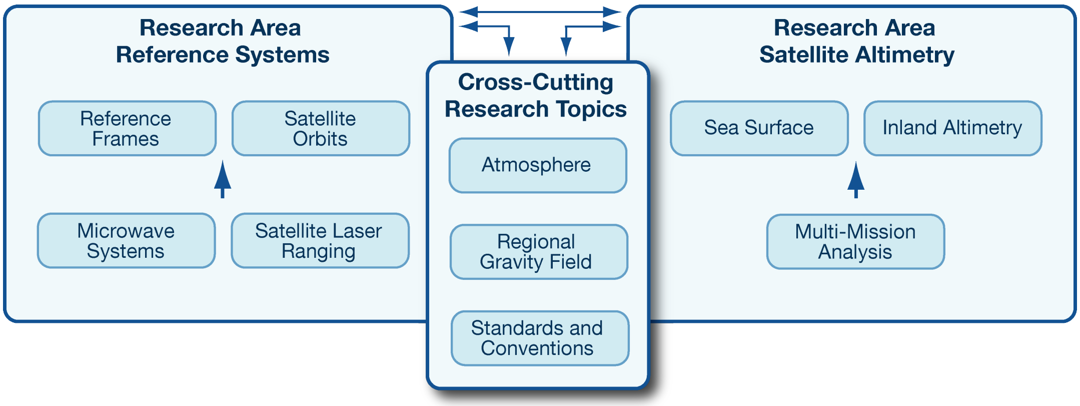

***Fig. 1:** Research Areas of the DGFI-TUM*

National and international involvement

The institute has a history of more than 65 years. Originally, it was established as DGFI in 1952 as an independent research facility at the Bavarian Academy of Sciences and Humanities (BAdW) in Munich. With effect from January 1, 2015 it has been integrated into the TUM. The institute has continuously been involved in various national and international research activities of which many were of high significance for the scientific advancement of geodesy. Its participation in geodetic-astronomical observations and electro-optical distance measurements for the determination of the German and European triangulation, its involvement in the first worldwide network of satellite triangulation, and its contribution to the development of dynamical methods of satellite geodesy for precise orbit determination, point positioning and gravity field modelling belong to the milestones of DGFI-TUM's history.

The DGFI-TUM is involved in various internationally coordinated research activities and collaborates intensively with various renowned research institutions all over the world. In particular, the institute recognizes the outstanding role of IAG's Scientific Services that form the backbone of national and international spatial data infrastructure. In this context, the DGFI-TUM operates data centers, analysis centers and research centers and has taken leading positions and supporting functions in IAG's Commissions, Projects, Working and Study Groups. Several scientists of the DGFI-TUM take leading positions in international scientific organizations (see Section 4.2). In IAG's Global Geodetic Observing System (GGOS) that coordinates the generation of high-quality science data products under predefined standards and conventions, the DGFI-TUM has a position of particular importance by chairing the GGOS Bureau of Products and Standards and two of the four GGOS Focus Areas (Section 3.2).

The DGFI-TUM also participates in research programmes of the European Union (EU) and the European Space Agency (ESA), and it cooperates in activities of the United Nations (UN). In this regard, the institute is currently involved in the implementation of a UN Resolution for a Global Geodetic Reference Frame (GGRF) and provides an IAG representative to the UN Working Group for the Global Geodetic Reference Frame (GGRF).

Research highlights of particular scientific and public interest

Several research results of the DGFI-TUM attained broad resonance in the scientific community and in the public during the year 2017. Among the scientific achievements, the following activities and publications can be highlighted.

- Validation of latest ITRS realizations: In the year 2016, DGFI-TUM released its latest realization DTRF2014 of the International Terrestrial Reference System (ITRS) in its role as an ITRS Combination Centre within the International Earth Rotation and Reference Systems Service (IERS). During 2017, thorough evaluations of the DTRF2014 and the latest releases of the other ITRS Combination Centers at IGN, France (ITRF2014) and JPL, USA (JTRF2014) were performed. Precise orbit determinations of ten high and low Earth orbiting satellites using Satellite Laser Ranging (SLR) over a total time span from 1993.0-2017.0 demonstrated that DTRF2014 and JTRF2014 with non-tidal loading (NTL) corrections perform best among the ITRS realizations for the satellites tested. The results have been published in the article *Evaluation of DTRF2014, ITRF2014, and JTRF2014 by Precise Orbit Determination of SLR Satellites*, IEEE Transactions on Geoscience and Remote Sensing, 2018, doi:10.1109/TGRS.2018.2793358); see also Section 1.3.

  Furthermore, investigations on the scales of Very Long Baseline Interferometry (VLBI) and SLR were performed, since the ITRF2014 reveals a scale bias between both techniques of 1.37 ppb (equivalent to a height shift at the Earth's surface of almost 1 cm).

This scale bias is not visible in the DTRF2014. The results of the scale investigations have been presented at the IAG-IASPEI Symposium 2017 in Kobe, Japan. Also the International VLBI Service and the International Laser Ranging Service (ILRS) compared three different ITRS realizations with their combined VLBI and SLR solutions, respectively. It was found that the DTRF2014 as well as the JTRF2014 do not show a long-term offset with respect to the combined VLBI and SLR solutions, whereas the ITRF2014 differs by about 0.7 ppb from both techniques with opposite sign; further details can be found in Section 1.4.

- First proposal for the station network of the International Height Reference System (IHRS): The implementation of the International Height Reference System is coordinated by the Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) within the GGOS Focus Area *Unified Height System* that is chaired by DGFI-TUM. This activity is supported by various IAG components and both GGOS Bureaus (Bureau for Networks and Communication/Bureau for Products and Standards; see Sect. 3.3). In 2017, a first proposal for the IHRS reference network has been prepared, comprising a global core network of about 170 stations co-located with geometric techniques, absolute gravity and tide gauges. The core network shall be densified by regional/national networks for local accessibility (*Vertical Datum Unification for the International Height Reference System (IHRS)*, Geophysical Journal International, 2017, doi:10.1093/gji/ggx025). For more information see Section 1.4.

- Special focus of altimetry research on polar oceans: Climate variations have a particularly strong impact on the ocean dynamics and sea level change in the Arctic and Antarctic Oceans. The monitoring of the polar oceans is consequently of high importance for understanding the impacts of the changes in the Earth's climate system. At the same time, the polar regions are very challenging for satellite altimetry since the occurrence of sea ice hinders the precise determination of sea surface heights. Advanced approaches for the classification of radar echoes to identify reliable measurements resulted in largely improved sea level records (*Monitoring the Arctic Seas: How Satellite Altimetry can be used to detect open water in sea-ice regions*, Remote Sensing, 2017, doi:10.3390/rs9060551). A 25-year-long multi-mission sea level product for the Arctic has been made freely available through the ESA Sea-Level Climate Change initiative (SL-CCI). Further details can be found in Section 2.2.

- Exploitation of Cryosat-2 SAR altimetry: Cryosat-2 is the first satellite equipped with a Delay-Doppler (also called SAR-) altimeter. This new and innovative measurement technique will be the standard technique on next generation altimetry missions. It enables the estimation of water heights with improved resolution and precision, but the exploitation of its full potential requires a dedicated data processing. In 2017, DGFI-TUM developed different approaches for the classification of Cryosat-2 SAR stack data and demonstrated applications of the data for Arctic lead detection and river level monitoring (*Lead Detection using Cryosat-2 Delay-Doppler Processing and Sentinel-1 SAR images*, Advances in Space Research, 2017, doi:10.1016/j.asr.2017.07.011; *River Levels Derived with CryoSat-2 SAR Data Classification - A Case Study in the Mekong River Basin*, Remote Sensing, 2017, doi:10.3390/rs9121238); see also Section 2.3.

- Implementation of the new GGOS Focus Area *Geodetic Space Weather Research*: The Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) implemented its fourth Focus Area in April 2017. After the Focus Area *Unified Height System* (see above), the new Focus Area *Geodetic Space Weather Research* is the second GGOS Focus Area that has been initiated and is chaired by DGFI-TUM scientists. The potential strength of severe space weather events and their impact on modern society, e.g. the interruption of satellite services including GNSS and communication systems, have brought several countries to recognize the necessity of studying these impacts scientifically. The programme of the new Focus Area consists of up to four joint study groups concentrating on (1) modelling the ionospheric electron density, (2) modelling the neutral density of the thermosphere, (3) studying the coupling processes between ionosphere and thermosphere, and (4) the impact on space weather on the aforementioned components; more details can be found in Section 3.1.

- Computation of real-time ionosphere maps within the EU Horizon 2020 project AUDITOR (Advanced Multi-Constellation EGNSS Augmentation and Monitoring Network and its Application in Precision Agriculture): The joint initiative of an international consortium of SMEs and universities aims at the implementation of a novel precise positioning technique – based on augmentation data – in a customized GNSS receiver. Among the key aspects are the development and implementation of sophisticated ionosphere models to increase the accuracy in real-time at the user side. Contributions of DGFI-TUM are focusing on the development of novel algorithms to provide enhanced ionospheric corrections. In 2017, a real-time regional model for the vertical total electron content (VTEC) for specific regions was developed and applied successfully; see Section 3.1.

1 Research Area Reference Systems

The work in this research area relies on the space geodetic observation techniques Very Long Baseline Interferometry (VLBI), Satellite and Lunar Laser Ranging (SLR/LLR), Global Navigation Satellite Systems (GNSS), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS). As a part of the Forschungsgruppe Satellitengeodäsie (FGS), DGFI-TUM contributes to the complete processing chain from operation of observing stations, data acquisition and provision, development of procedures and theoretical models, data analysis and combination, and parameter determination. Among the institute's core products are highly accurate regional and global realisations of three-dimensional geodetic reference systems that are determined from the combination of the above-mentioned space geodetic observation techniques.

The work benefits from DGFI-TUM's engagement in the international scientific services of the International Association of Geodesy (IAG). Mostly by virtue of long-term commitments, DGFI-TUM operates data centres, analysis centres, and research centres within the IAG. This ensures the direct access to the original data of the space geodetic techniques and to the products generated by the scientific services. Table 1.1 summarises the activities that are closely related to this research area.

Table 1.1: *Long-term commitments of DGFI-TUM in IAG Services that are related to this research area.*

IAG Service	DGFI-TUM Commitments
International Earth Rotation and Reference Systems Service (IERS)	International Terrestrial Reference System (ITRS) ITRS Combination Centre
International GNSS Service (IGS)	Regional Network Associate Analysis Centre for SIRGAS (RNAAC-SIR), Tide Gauge Monitoring Working Group (TIGA)
International Laser Ranging Service (ILRS)	Global Data and Operation Centre (EDC), Analysis Centre
International VLBI Service for Geodesy and Astrometry (IVS)	Analysis Centre, Combination Centre (together with BKG)

The research in this field is supported by several projects funded by the Deutsche Forschungsgemeinschaft (DFG) and the European Space Agency (ESA) (see Table 1.2).

Table 1.2: *Projects that are related to this research area.*

Project	Title	Funding
Project PN5	Consistent celestial and terrestrial reference frames by improved modelling and combination (Research Unit FOR 1503)	DFG
Project PN6	Consistent dynamic satellite reference frames and terrestrial geodetic datum parameters (Research Unit FOR 1503)	DFG
DIGERATI	Direct Geocentric Realisation of the American reference frame by combination of geodetic observation techniques	DFG
CIEROT	Combination of space geodetic observations for estimating cryospheric mass changes and their impact on Earth rotation	DFG
ESA-EOP	Independent generation of Earth Orientation Parameters	ESA

1.1 Analysis of Space-Based Microwave Observations

VLBI data analysis

The DGFI-TUM is one of the operational Analysis Centres (AC) of the International VLBI Service for Geodesy and Astrometry (IVS). In this role, the institute regularly computes and provides VLBI solutions, in particular for IVS rapid turnaround EOP sessions (R1 and R4). For many years, those data were computed with the dedicated VLBI analysis software OCCAM. In 2017, DGFI-TUM switched from OCCAM to the newly developed proprietary software DOGS-RI. DOGS-RI is an extension for Radio Interferometry of the DGFI Orbit and Geodetic parameter estimation Software (DOGS). The new software incorporates the current international standards as defined by the International Earth Rotation and Reference Systems Service (IERS) 2010 Conventions. Furthermore, as part of the general DOGS package, DOGS-RI provides a flexible framework for VLBI analysis in consistency with the other space geodetic techniques analysed and combined by DGFI-TUM.

Before DGFI-TUM entered into routine operations with DOGS-RI, the results had to undergo various tests in order to demonstrate their quality and reliability. All kinds of VLBI sessions from the years 2003 to 2016 (in total 1951 sessions) have been reprocessed with DOGS-RI, and the solutions have been compared to those of OCCAM (see Kwak et al. 2017 and Fig 1.1). For both Terrestrial Reference Frame (TRF) and Earth Orientation Parameters (EOP) the agreement was within the sub-mm level (except for the nutation offset dY, where OCCAM created an unexpected drift that is not visible in DOGS-RI). Currently, the IVS Combination Centre conducts further external validations against the individual VLBI solutions of other IVS ACs and also against combined solutions.

Another important progress in the year 2017 was the implementation of the new vgosDB-format for VLBI data (which replaces the previous NGS-format). The completion of this task is expected for early 2018.

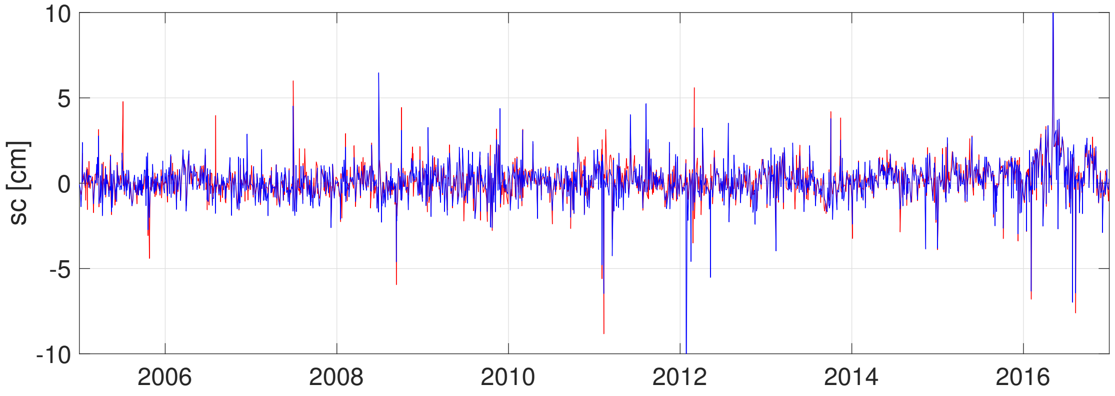

Fig. 1.1: The time series of the scale parameters from DOGS-RI (blue) and OCCAM (red) solutions.

Monitoring of regional deformations with GNSS

Since 1998, DGFI-TUM has installed 21 continuously operating GNSS (CO-GNSS) stations in Europe and South America; 11 of these stations are still under the responsibility of DGFI-TUM, while the others were formally transferred to local institutions to facilitate their operability. Five stations were installed along the Bavarian Alps in the frame of the European Union's Territorial Cooperation (INTERREG III) Alpine Space Project for detection and control of crustal deformations in the Alpine region (ALPS-GPS QUAKENET). Although this project ended in 2007, three DGFI-TUM stations continue delivering measurements and are included in different European geodetic projects. The other stations contribute to various international initiatives, especially to the IGS Tide Gauge Benchmark Working Group (TIGA), the IGS Multi-GNSS Experiment (MGEX), and the regional densification of the ITRF in Latin America (SIRGAS). Based on the analysis of precise station position time series, DGFI-TUM investigates the best possible strategy to model consistently three main components: (1) a linear component to derive horizontal and vertical displacement fields that serve as the basis for monitoring regional surface deformations; (2) earthquake-related discontinuities to identify deformation patterns associated to inter-seismic, co-seismic and post-seismic effects; and (3) seasonal components to infer transient surface deformations caused by atmospheric and hydrological loading.

1.2 Analysis of Satellite Laser Ranging Observations

SLR data analysis

As one of the presently seven active analysis centres (AC) of the ILRS Analysis Standing Committee (ILRS/ASC) DGFI-TUM processes on a daily basis weekly arcs of the two LAGEOS and Etalon satellites, using tracking data until the day before. This solution contains station coordinates and Earth orientation parameters (EOPs). The ILRS/ASC Combination Centers combine the individual solutions to the official product which is mainly used for the rapid EOP service.

As an additional product a weekly solution with the same orbit characteristics but with slightly more data, due to a delay of 2.5 days between the last measurement and processing, is used for reference frames. This product also includes orbits in the "sp3-format" to the LAGEOS and Etalon satellites. DGFI-TUM also contributes to the pilot projects of the ILRS/ASC on the estimation of range biases for all stations. Additionally, DGFI-TUM processes all spherical satellites and some non-spherical satellites on a regular basis for various applications, see Sect. 1.3.

SLR quality control

One of the error sources in SLR observations are system biases, mainly range biases, which have a direct influence on the scale of the resulting station coordinates. The Quality Control Board (ILRS/QCB) is a joint activity of the Analysis Standing Committee (ASC) and the Network and Engineering Standing Committee (NESC). Its goal is to quickly provide feedback to the tracking station operators in case of unexpected data anomalies, and to support them in maintaining the data quality. The board meets monthly, mostly via teleconferences. Another task of the QCB is to develop strategies to detect systematics in the data delivered by the ILRS tracking stations.

The DGFI-TUM performs the daily processing of station biases on a pass-by-pass basis for most of the relevant geodetic satellites. In case of bias anomalies, the respective station is contacted via ILRS Rapid Service Mail. In 2017, only 5 bias alerts were issued by the Quality Control (Q/C) centres. This indicates that the tracking quality has largely improved over the last years (up to 30 alerts per year). Weekly files per satellite are available from our website ilrs.dgfi.tum.de/index.php?id=37/. Additionally, the website contains time series of biases and the analysis of the remaining residuals of all current tracking stations. Graphics show the pass by pass biases and running averages that are generally smoother and allow for a better identification of trends. From the plots it was obvious that the centre of mass corrections (CoM) for

Ajisai and the Etalon satellites are apparently wrong for a number of stations. Figure 1.2 shows the running averages of the range biases for the station Wettzell using SLRF2014 coordinates between 2015 and 2018. It can clearly be seen that the Ajisai biases are off by 4 cm and the Etalons are off between 2–3 cm from the average of the other satellites. These results indicate that the CoM-corrections for Ajisai and Etalon require a revision. During this processes it was detected that the CoM-corrections to all satellites have to be revised.

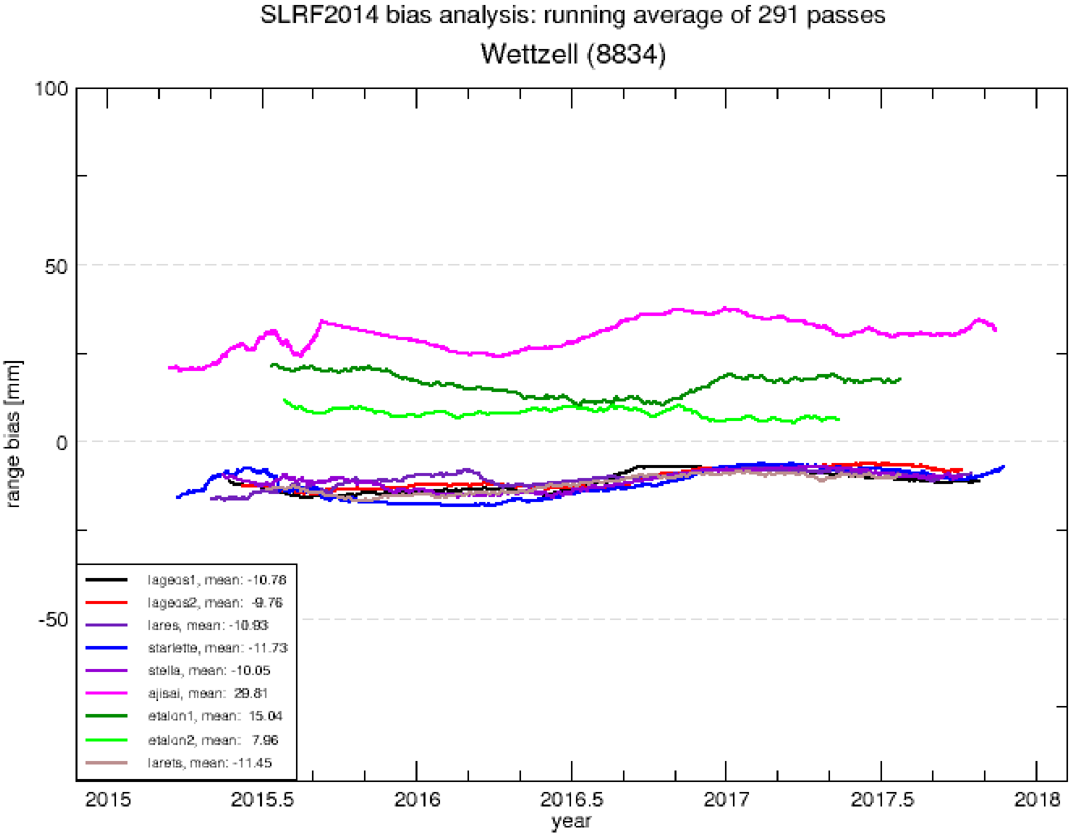

***Fig. 1.2:** An example of the station bias plots available at the DGFI-TUM web site.*

Further studies concentrated on the behaviour of the remaining residuals after range biases have been corrected. An equal distribution along the azimuth and the elevation was expected, but a few stations showed an inhomogeneous structure in the range of a few millimetres. For example, the residuals of station Monument Peak (7110) show a structure around the azimuth of 0 degree (Fig. 1.3), whereas the station Potsdam (7841) show a small elevation dependency (Fig. 1.4). The azimuth dependency could be caused by a deficit in the modelling of the orbit since most of the anomalies occur at azimuths of 0, 90 or 180 degrees. The elevation dependency could be caused by incorrect atmospheric reductions or by an inaccurate modelling of the tropospheric correction.

SLR data management

Since the foundation of the International Laser Ranging Service (ILRS) in 1998, the EUROLAS Data Centre (EDC) operated by DGFI-TUM acts as one of two global ILRS data centres (the second one is the Crustal Dynamics Data Information System, CDDIS, operated by NASA). The EDC, as an ILRS Operation Center (OC) and ILRS Data Center (DC) has to ensure the quality of submitted data sets by checking their format. Furthermore, a daily and hourly data exchange with the NASA OC and CDDIS is performed. All data sets and products are publicly available for the ILRS community via ftp (ftp://edc.dgfi.tum.de) and the dedicated website edc.dgfi.tum.de.

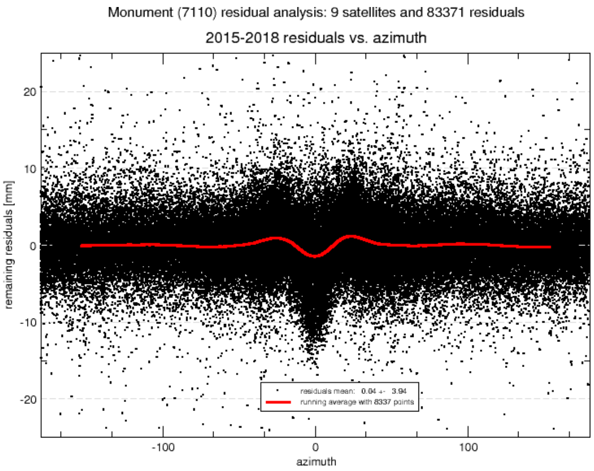

Fig. 1.3: *Station Monument Peak (7110) azimuth dependency of residuals.*

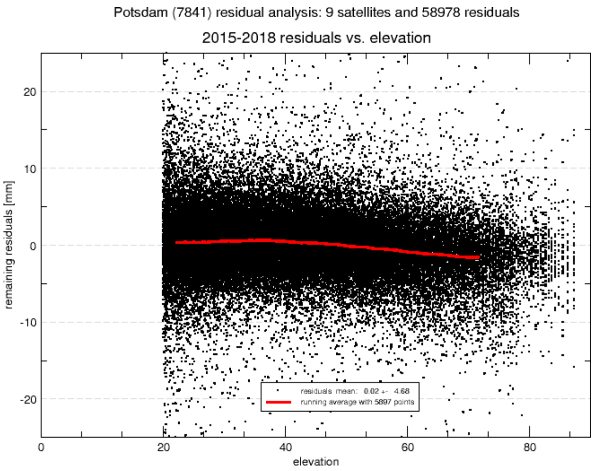

Fig. 1.4: *Station Potsdam (7841) elevation dependency of residuals.*

EDC is running several mailing lists for the exchange of information, data and results. In 2017, 52877 Consolidated Prediction Format (CPF) files of 98 satellites were sent automatically to SLR stations. Besides, EDC distributed SLR-Mails (54 messages in 2017), SLR-Reports (1195 in 2017) and Urgent and Rapid-Service-Mails (5 in 2017). In 2017, 42 SLR stations observed 97 different satellites. There were 5 new satellite missions tracked by SLR stations, namely Glonass-137, QZS-2, QZS-3, QZS-4 and Technosat. In 2017, an updated specification of the format for CRD, CPF and site log has been developed and will be officially introduced in 2018.

1.3 Computation of Satellite Orbits

Impact of TRF realizations on precise orbit determination (POD)

An ITRS realization is a basis for precise monitoring global change phenomena, such as tectonic motion and deformations, postglacial rebound, global and regional sea level change, Earth's rotation, precise positioning applications on and near the Earth's surface, precise orbit determination (POD) and other applications. Three new ITRS realizations have been released recently: ITRF2014, DTRF2014 and JTRF2014. These ITRS realizations have been used for POD of ten high and low Earth orbiting geodetic satellites (altitudes between 680 and 19130 km) using SLR over a total time span from 1993.0 to 2017.0. It was found that all new ITRS realizations perform better than the previous realization for SLR stations – SLRF2008. In this time span, the mean values of the SLR orbit fits are on average reduced (improved) by 3%, 3.6%, 8.1%, and 7.7% for ITRF2014, DTRF2014, DTRF2014 with non-tidal loading (NTL), and JTRF2014, respectively. The improvement of the RMS fits is even larger at 2015.0–2017.0: 14% for ITRF2014 and 15.5% for DTRF2014. Using SLRF2008 causes increasing with time (after 2009) RMS fits of observations (Fig. 1.5, left), since this realization was derived using data until 2009.0 only, while the latest ITRS realizations were derived using the data until 2015.0 and, therefore, more precisely provide station motions after 2009.0 than their predecessors. The ITRF2014 and SLRF2008 show a trend of 0.16 and 0.28 mm/y in the mean fits of observations for LAGEOS-1 (not shown here) and Starlette (Fig. 1.5, right), respectively, at the time span 2001.0–2017.0. More results are given in Rudenko et al., 2018. From our analysis, we conclude that DTRF2014 with NTL corrections and JTRF2014 (with the editing for SLR stations Concepcion and Zimmerwald as described in the cited article) show the best performance among the ITRS realizations for the satellites tested. They are recommended to be used.

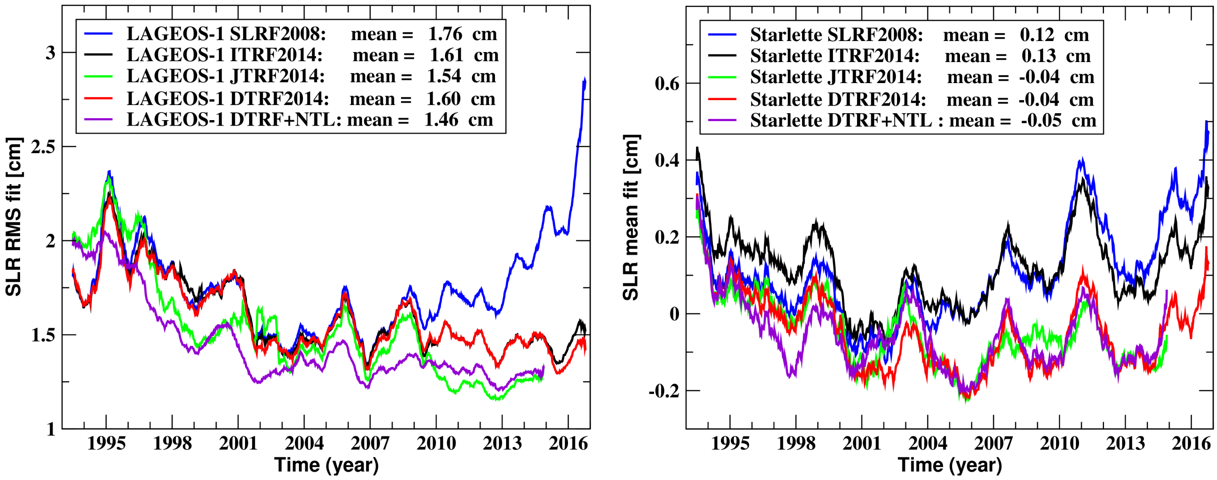

Fig. 1.5: *(Left) 50-week running averages of the RMS fits of SLR observations (in cm) for LAGEOS-1 orbits derived using SLRF2008, ITRF2014, JTRF2014, DTRF2014 linear, and DTRF2014+NTL. (Right) 50-week running averages of the mean fits of SLR observations (in cm) for Starlette orbits derived using SLRF2008, ITRF2014, JTRF2014, DTRF2014 linear, and DTRF2014+NTL.*

Refined modelling of thermospheric drag (DFG project INSIGHT)

SLR observations to the spherical satellites ANDE-P, ANDE-C and SpinSat were used to scale the thermospheric density provided by five empirical models CIRA86, NRLMSISE00, JB2008, DTM2013, and GFZ CH-Therm-2017 and, thus, to improve the information about the thermospheric drag acting on these satellites. A more detailed description on this project is given in Section 3.1 (research topic Atmosphere).

SLR multi-satellite solution

The work in this topic is closely related to project PN6 “Consistent dynamic satellite reference frames and terrestrial geodetic datum parameters” within DFG Research Unit FOR1503 “Space-time reference systems for monitoring global change and for precise navigation in space”. Geodetic parameters such as weekly 3-D station coordinates, Earth orientation parameters (EOP), and selected weekly Earth’s gravity field (Stokes) coefficients up to degree and order six were consistently determined from SLR measurements to up to 11 geodetic satellites. The analysed SLR constellation consists of LAGEOS-1/2, Etalon-1/2, Stella, Starlette, Ajisai, Larets, LARES, BLITS and WESTPAC. Observations cover a time span of 38 years from February 16, 1979 to April 30, 2017. If multiple satellites with various altitudes and orbit inclinations are combined, correlations between the estimated parameters can significantly be reduced. This allows for estimating more reliable parameters with higher precision than by using the four-satellite standard constellation (LAGEOS-1/2, Etalon-1/2) that is currently being analysed by the ILRS for the determination of TRF and EOP. In particular, the Stokes coefficients, EOP and TRF datum parameters (3 translations, 3 rotations, 1 scale factor), which are highly correlated with satellite-specific orbit parameters, are significantly improved.

As an example, Fig. 1.6 shows the improvement for weekly gravity field coefficient solutions of the SLR multi-satellite solutions w.r.t. the four-satellite solution. Different five-satellite solutions show different improvements which depend on the orbit characteristics of the respectively added satellite. In our 11-satellite solution, all coefficients are significantly improved by at least 40%. For the degree 5, as well as for degree 4, 6, and order 1 coefficients the improvement reached almost 100%. More details on the SLR multi-satellite solution have been published by Bloßfeld et al. (2018).

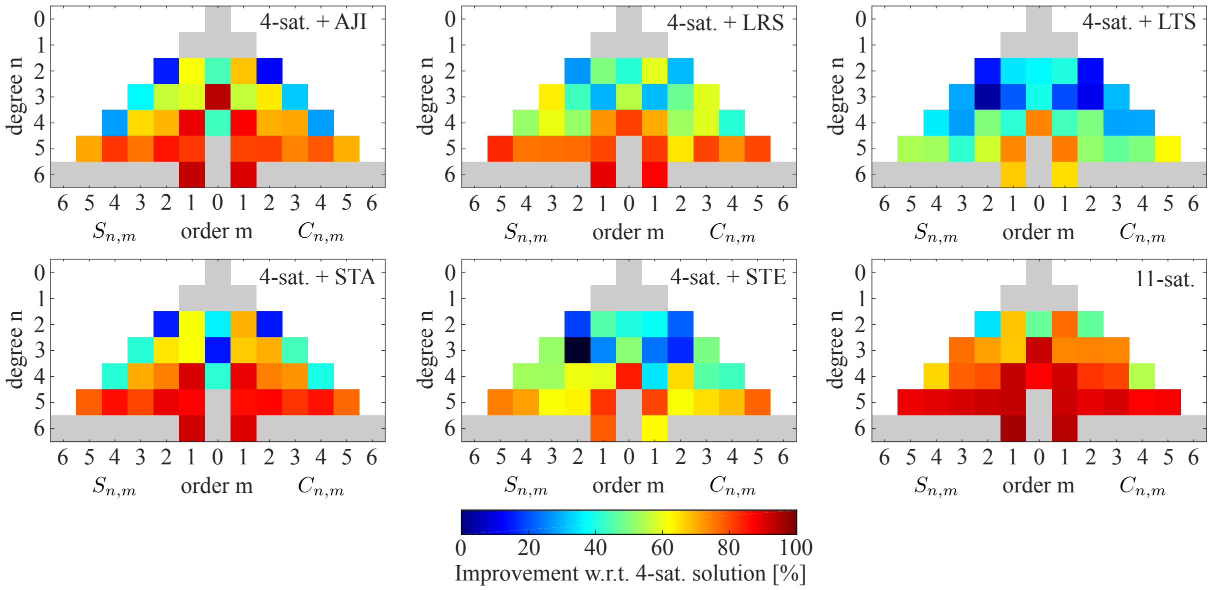

Fig. 1.6: *Improvements of the WRMS over the weekly gravity field coefficient solutions w.r.t. the four-satellite standard solution. Coefficients marked in gray have not been estimated.*

1.4 Determination of Reference Frames

DGFI-TUM realization of the International Terrestrial Reference System (ITRS): DTRF2014

The most recent ITRS realizations computed by the ITRS Combination Centres of the IERS are the DTRF2014 (DGFI-TUM), ITRF2014[1] (IGN, France) and JTRF2014[2] (JPL, USA). These three ITRS realizations are based on identical input data, i.e. observations of the space geodetic techniques VLBI, SLR, GNSS and DORIS. However, the parametrization of the frames differs conceptually: While DTRF2014 and ITRF2014 are based on station positions at a reference epoch and corresponding velocities, the JTRF2014 is based on time series of station positions. Further, the combination strategies applied for DTRF2014 and ITRF2014 differ with respect to the combination level: The ITRF2014 is based on the combination of solutions, the DTRF2014 is computed by the combination of normal equations.

DGFI-TUM's ITRS realization DTRF2014 comprises 3D coordinates and coordinate changes of 1347 GNSS-, 113 VLBI-, 99 SLR- and 153 DORIS-stations. The DTRF2014 solution is available in one comprehensive SINEX file and four technique-specific SINEX files. A detailed description of the solution is given on the website of DGFI-TUM (www.dgfi.tum.de/en/science-data-products/dtrf2014/, see also Seitz et al., 2016 and Bloßfeld et al., 2017).

In 2017, detailed comparisons of the three different ITRS realizations have been performed. A major focus was on the investigations of the VLBI and SLR scale, since a bias of 1.37 ppb between both techniques in the ITRF2014 was reported by Altamini et al. (2016). Technique-specific similarity transformations have been performed between the ITRF2014 and DTRF2014 (see Fig. 1.7). The results of this external comparison indicate that there is a scale offset

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[1] Altamimi Z., Rebischung P., Metivier L., Xavier C.: ITRF2014: A new release of the International Terrestrial Reference Frame modeling nonlinear station motions, J. Geophys. Res. Solid Earth, 121, doi:10.1002/2016JB013098, 2016

[2] Abbondanza C., Chin T., Gross R., Heflin M., Parker J., Soja B., van Dam T., Wu X.: JTRF2014, the JPL Kalman filter and smoother realization of the International Terrestrial Reference System, J. Geophys. Res. Solid Earth, 122, doi:10.1002/2017JB014360, 2017

between SLR and VLBI of about 8 mm (= 1.2 ppb). Since such a scale offset between SLR and VLBI is not visible in the DTRF2014 solution, the result confirms the scale bias in the ITRF2014. Various investigations on this scale issue have been performed at DGFI-TUM, which were reported at the IAG-IASPEI Scientific Assembly 2017 in Kobe, Japan. A publication on these scale results have been submitted for publication in the IAG Symposia Series by Springer.

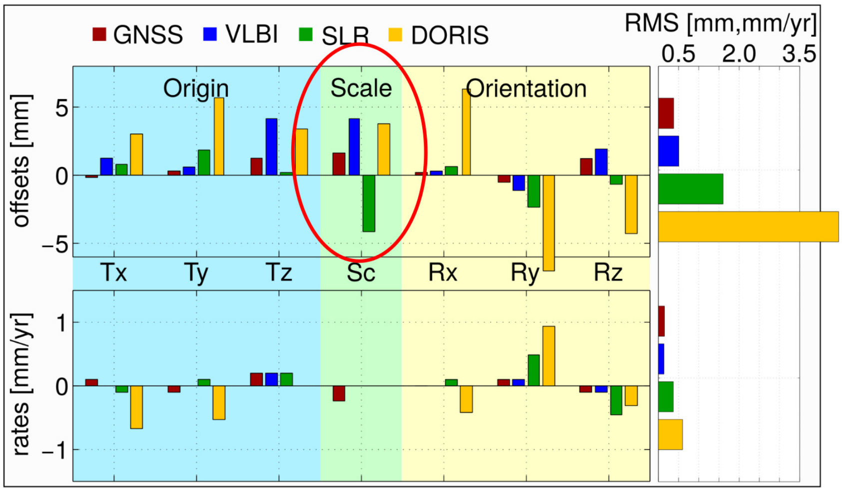


Fig. ***1.7:*** *Results of technique-specific 14-parameter Helmert transformations between DTRF2014 and ITRF2014.*

To further investigate the scale bias between VLBI and SLR, the three ITRS realizations were compared with the combined VLBI and SLR solutions obtained by the Combination Centers (CC) of the IVS and ILRS, respectively. The IVS CC located at BKG (Germany) provided Fig. 1.8, which shows epoch-wise estimated scale parameters of the IVS combined solutions (VLBI-only) w.r.t. several different TRF realizations. It is clearly visible that the DTRF2008, the DTRF2014, the JTRF2014, and the quarterly VLBI-only TRF solution VTRF2015q2 agree quite well with the IVS combined solutions showing a mean value close to 0. The ITRF2008 as well as the ITRF2014 show a mean bias of about 0.5 ppb. Similar investigations have been performed for SLR. The primary ILRS CC located at ASI (Italy), named ILRSA in the following, provided epoch-wise estimated scale parameters of combined ILRSA solutions w.r.t. the most recent ITRS realizations (Fig. 1.9). Again, the DTRF2014 as well as the JTRF2014 do not show a long-term mean offset w.r.t. the SLR-only solutions whereas the ITRF2014 shows a mean offset of about 0.7 ppb. This means that the DTRF2014 and the JTRF2014 do not distort the scale of the SLR subnet.

As a conclusion of these investigations, we can state that DTRF2014 does not contain the scale bias between VLBI and SLR that is visible in the ITRF2014. The scale issue remains a key topic for TRF research which is a prerequisite for future ITRF computations and their accuracy.

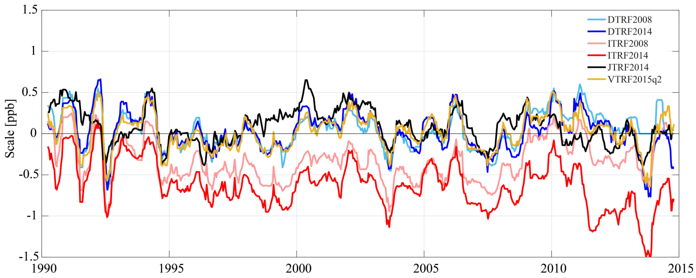


Fig. 1.8: *Scale of combined IVS solutions w.r.t. different TRF realizations. This plot has been kindly provided by S. Bachmann (IVS CC at BKG, Germany).*

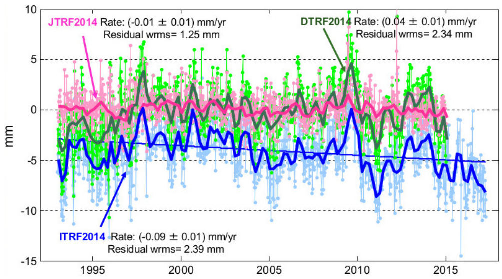


Fig. 1.9: *Scale of combined ILRSA solutions w.r.t. different TRF realizations. This plot has been kindly provided by C. Luceri (ASI, Italy).*

Regional terrestrial reference frame in Latin America (SIRGAS)

The primary objective of SIRGAS (Sistema de Referencia Geocéntrico para las Américas) is the determination and maintenance of a reliable reference frame in Latin America as a densification of the ITRF and as a regional realization of the ITRS. DGFI-TUM's research is focused on designing the best strategy to guarantee the reliability of the regional reference frame as it is frequently affected by strong earthquakes. We are investigating the possibility of using SLR observations for the realization of the geocentric datum in the GNSS network (see project DIGERATI). Further, we are developing methodologies to incorporate seismic discontinuities in the computation of the GNSS-based reference frame realization to support the precise transformation of coordinates referring to pre-seismic and post-seismic frame solutions (Sánchez 2017). SIRGAS is at present realized by 425 GNSS stations that are processed on a weekly basis to generate instantaneous weekly station positions aligned to ITRF and multi-year (cumulative) reference frame solutions. Instantaneous weekly positions are especially useful when strong earthquakes cause co-seismic displacements or strong relaxation motions at the SIRGAS stations disabling the use of previous coordinates. The multi-year solutions provide the most accurate and up-to-date SIRGAS station positions and velocities. They are used for the realization and maintenance of the SIRGAS reference frame between two releases of the ITRF. While a new ITRF release is published more or less every five years, the SIRGAS reference frame multi-year solutions are updated every one or two years. Figure 1.10 shows the horizontal component of the latest multi-year solution (SIR17P01: from April 2011 to January 2017) and its comparison with the previous one (SIR15P01: form April 11 to February 2015). The reference frame distortions caused by the recent earthquakes occurred in the region are evident.

DGFI-TUM acts as the IGS Regional Network Associate Analysis Centre for SIRGAS (IGS RNAAC SIR) and makes the SIRGAS science data products available via www.sirgas.org and ftp.sirgas.org. The DGFI-TUM research related to SIRGAS is accompanied under a strong international cooperation with Latin American organizations.

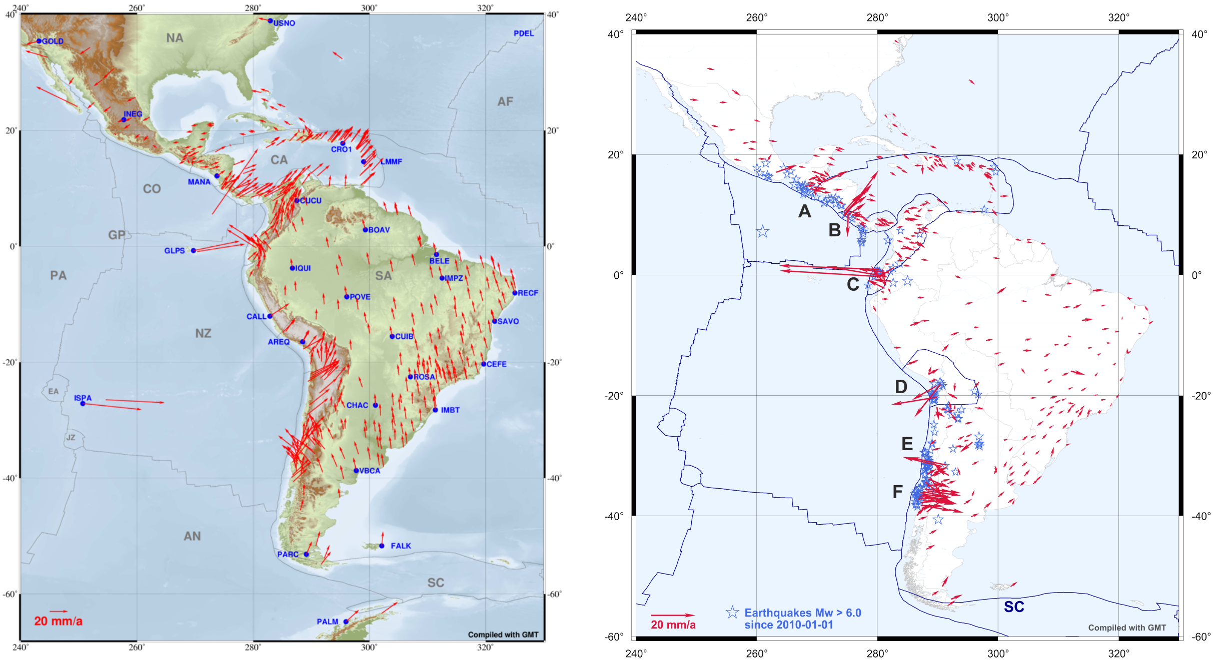


Fig. 1.10: Horizontal velocities of the SIRGAS reference frame realization SIR17P01 (left) and its comparison with the previous realization SIR15P01 (right). Large discrepancies are caused by strong earthquakes: (A) Guatemala Mw7.4 2012-11-11, (B) Nicoya Mw7.6 2012-09-05, (C) Pedernales Mw7.8 2016-04-16, (D) Iquique Mw8.2 2014-04-01, (E) Illapel Mw8.3 2015-09-16, (F) Post-seismic relaxation El Maule Mw8.8 2010-02-27.

DFG project DIGERATI

The DFG project DIGERATI (Direct Geocentric Realisation of the American Reference Frame by Combination of Geodetic Observation Techniques) aims at the realization of the South and Central American reference frame by a sequence of Epoch Reference Frames (ERFs). The ERFs will be realized directly by combination of the geodetic techniques SLR, VLBI, and GNSS.

As SLR is a key space technique for the realization of the geodetic datum of terrestrial reference frames, the focus has been on the effects of a potential future development of the global SLR station network on the accuracy of the required geodetic parameters. Within a simulation study, a potential future SLR station network has been compared to the current situation (Fig. 1.11). The effect of a better network geometry as well as different scenarios of improved station performances have been evaluated (Kehm et al., 2017). Fig. 1.12 shows the results for a scenario assumed to be realistic for the near future: the current network extended by eight stations, and the performance of each station raised to at least 20%. It was found (Kehm et al. 2017) that establishing additional stations and improving the performance of the existing network have to go hand in hand in order to determine stable ERFs.

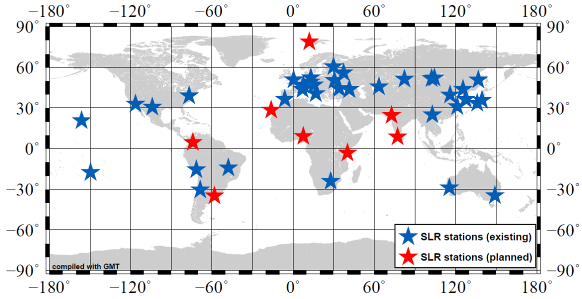


Fig. 1.11: *Existing and potential future SLR station network as assumed in the simulation studies.*

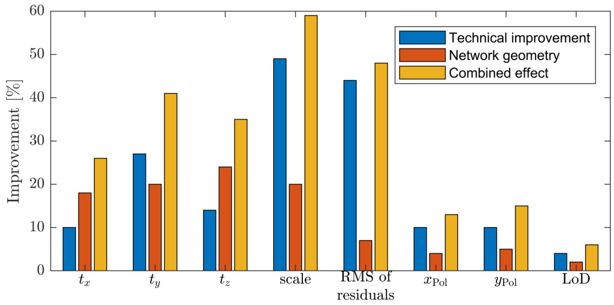


Fig. 1.12: *Improvement of the WRMS of the Helmert Parameters, of the RMS of the residuals of the Helmert transformation as well as of the WRMS of the EOP.*

DIGERATI will combine SLR, VLBI and GNSS in order to investigate the optimum set-up for an ERF. Presently, a global GNSS network with all SIRGAS and a subset of selected global stations is being processed. Next steps will focus on the strategy for combining the different station networks via co-location stations (Fig. 1.13).

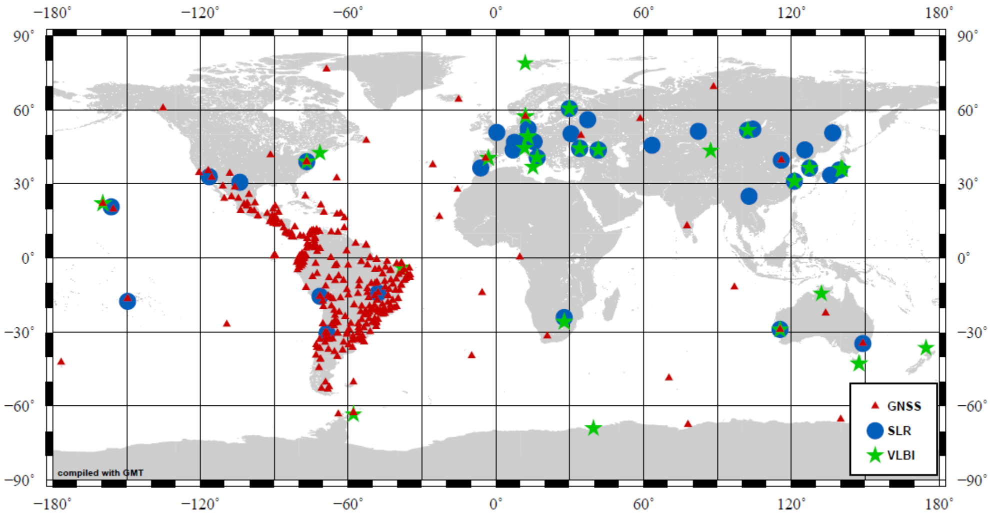


Fig. 1.13: *Station network for realizing an ERF in Latin America featuring all ILRS and IVS stations and a GNSS network of the SIRGAS plus a subset of global IGS stations.*

Consistent realization of terrestrial and celestial reference systems

The consistency between the realizations of the global Terrestrial Reference Frame (TRF), the Celestial Reference Frame (CRF) and the Earth orientation parameters (EOP) is of highest importance for a variety of scientific and practical applications. Systematic drifts or biases between TRF, CRF and EOP cause errors in positioning, navigation or orbit determination that are well within today's measurement accuracy. Hence, the consistent determination of the related reference frame and Earth orientation parameters from the combined analysis of the space-geodetic observing techniques VLBI, SLR, GNSS, DORIS has been identified as an extremely important task within IAG and IUGG: In its Resolution R3 (2011) the IUGG urges that the highest consistency between the ITRF, ICRF and EOP should be a primary goal in all future realizations. So far, the standard ICRF solutions are based on VLBI only.

The DGFI-TUM worked intensively into the direction of this requirement during the past years. In 2017, within the project "Consistent celestial and terrestrial reference frames by improved modelling and combination" as part of the DFG Research Unit FOR1503 "Space-time reference systems for monitoring global change and for precise navigation in space", we obtained the first simultaneous and consistent realization of TRF, CRF and EOP (Kwak et al., 2018) in accordance with the IUGG Resolution.

The joint parameter estimation was based on homogeneously processed VLBI, GNSS, and SLR single solutions for 11 years (2005.0–2016.0). Seven types of combined solutions were computed following the selections of different local ties (LTs), EOP combination setups, and different weights of the techniques (Table 1.3).

Table 1.3: *Solution setups to investigate different impacts on a consistent realization of TRF, CRF and EOP.*

solution	ΔLT [mm] / Δv [mm/yr]	combined EOP	weighting of techniques
A	30 / 1.5	all	equal weights
B	100 / 5.0	all	equal weights
C	1000 / 1000	all	equal weights
D	30 / 1.5	VLBI-only, SLR/GNSS	equal weights
E	30 / 1.5	ΔUT only	equal weights
F	30 / 1.5	x/y-pole only	equal weights
G	30 / 1.5	all	$\lambda_{\text{VLBI}} = 0.1$

The impacts of the different combination setups on CRF, TRF, and EOP were investigated. The following conclusions were derived (more details are reported in Kwak et al., 2018):

- The combination of different space geodetic techniques improves the precision of the estimated parameters due to the larger number of observations.
- The CRF benefits from the precise terrestrial x/y-pole coordinates estimated by GNSS (Fig. 1.14).
- The combination of ΔUT1 from VLBI and the satellite techniques affects the right ascension and therefore the CRF z-rotation (Fig. 1.14).
- It became evident that the common determination of TRF, CRF and EOP systematically influences future CRF computations at the level of several μas.

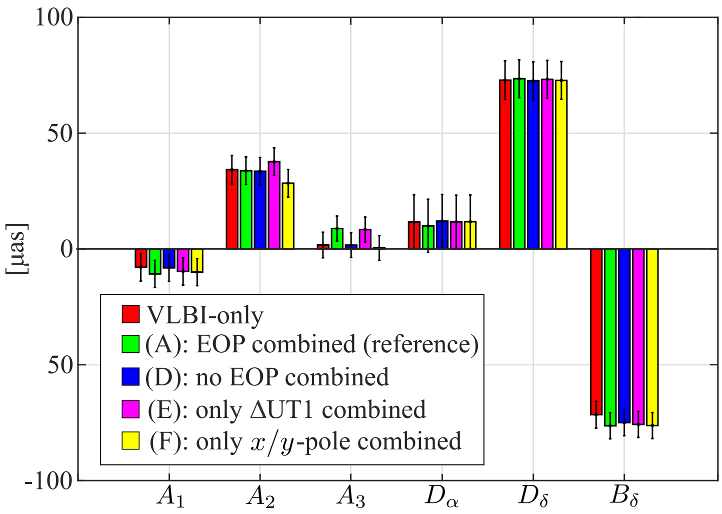


Fig. 1.14: *CRF transformation parameters and their standard deviations (error bars) of VLBI-only and different EOP combination setups w.r.t. ICRF2.*

ESA-EOP project - Independent generation of Earth Orientation Parameters

Earth Orientation Parameters (EOP) are fundamental geodetic parameters describing the orientation of the Earth in space, i.e., the transformation between the terrestrial and the celestial reference frame (Fig. 1.15). Thus, their precise knowledge is indispensable for various geodetic applications such as the realization of reference and time systems, precise orbit determination, positioning and navigation.

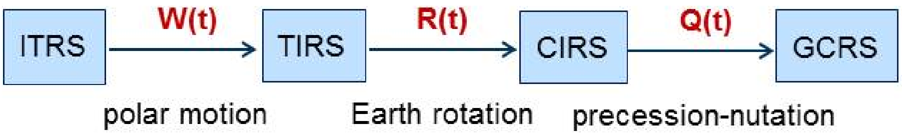


Fig. 1.15: *Transformation between the ITRS and the GCRS described by the EOP.*

DGFI-TUM leads the ESA project “Independent generation of Earth Orientation Parameters” (ESA-EOP) the started in 2017. The project aims at the realization of a scenario for the generation of final, rapid, and predicted EOP products by combining the four space geodetic techniques GNSS, SLR, DORIS, and VLBI at highest precision. A prototype software shall be developed for this purpose.

The project includes partners from the TUM (DGFI-TUM and the Chair of Satellite Geodesy) as well as the Bundesamt für Kartographie und Geodäsie (BKG), the Deutsches Geoforschungszentrum Potsdam (GFZ), and the TU Vienna. The work of DGFI-TUM is focused in particular on the survey of the state of the art of the generation of EOP products, the analysis of SLR contributions, the study of different combination methods, and the development of the combination software for final EOP products.

Within the first task, a literature survey and a review of ESA’s current involvement in reference frame and EOP activities have been performed. An inventory of ESA’s processing standards for the IAG services (ILRS, IVS, IGS) has been set up in order to identify areas for improvement or inconsistencies that need to be solved for in an integrated processing approach. First investigations on the quality of ESA’s current contribution to the combined ILRS EOP products (weekly ILRS-A solution) as well as on the impact of different mean pole models on the SLR-based

EOP solutions have been performed. Fig. 1.16 shows the conceptual work flow for the EOP combination and prediction software development which has been elaborated. In the ongoing process, DGFI-TUM will be responsible for the development of the final EOP product software tools enabling a combination on normal equation (NEQ) or on parameter (solution) level. A feedback loop between all project partners and ESA will ensure that all processing standards and software tools will meet the requirements identified or defined within the ongoing process.

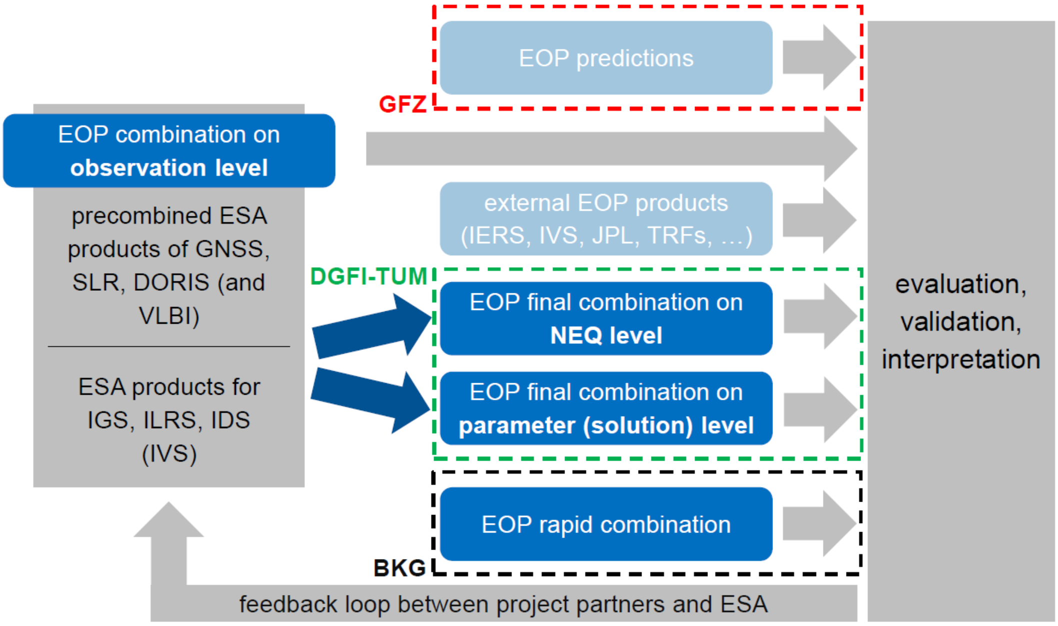


Fig. 1.16: *Proposed combination scenarios within this project.*

DFG project CIEROT

The goal of this project is the combined analysis of different satellite techniques to estimate cryospheric mass changes and their impact on Earth rotation. Among the analysed data sets are time variable gravity field models of the satellite mission GRACE (Gravity Recovery and Climate Experiment). Changes of the Earth's gravity field are caused by mass displacements. They can be used to determine effective angular momentum functions (so-called χ-functions) that are connected with the mass-related changes of Earth rotation. By applying suitable filter techniques, the GRACE observations can be separated into the contributions of oceans, continental hydrosphere and the cryosphere. But the GRACE-derived effective angular momentum functions suffer from uncertainties due to (1) the required destriping and filtering of the GRACE data, (2) leakage in the course of the separation of individual contributions, (3) the reduction of the effect of glacial isostatic adjustment (GIA), and (4) the required replacement of the erroneous gravity field (Stokes) coefficients C_{10}, C_{11}, S_{11} and C_{20}.

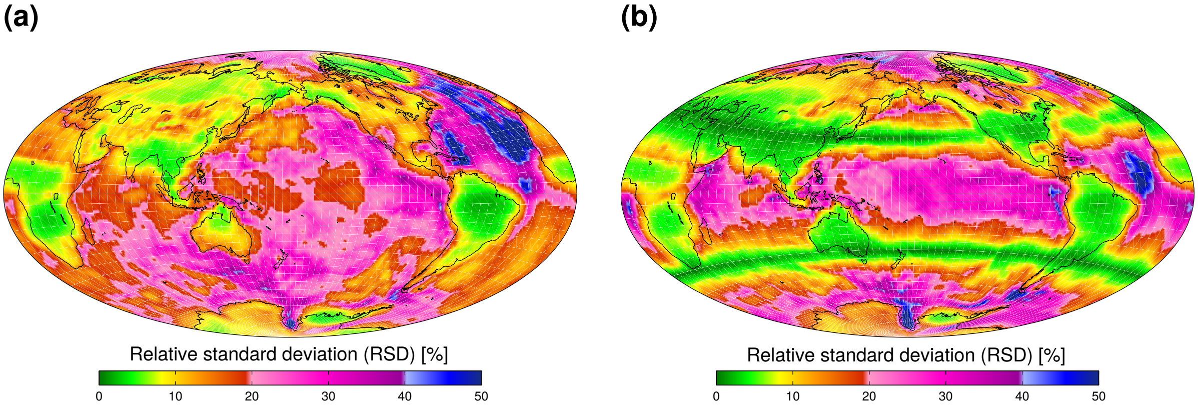
Figure 1.17 shows that the degree-1 Stokes coefficients affect in particular the mass estimates in the North Atlantic (50%), mountain areas (18%) and Antarctica (18%). Hence, the estimation of the χ_2 component of the oceanic mass effect χ^O shows the largest uncertainties of about 5.2 mas (24%). The impact on the hydrological mass effect χ^H is also quite high 3.9 mas (23%) due to the fact that the hydrological mass effect is significantly smaller than the oceanic one. The influence on the Antarctic mass effect χ^A is smaller (up to 0.4 mas; 7%).

Table 1.4: *Mean empirical errors (σ, [mas]) and relative standard deviations (RSD, [%]) of GRACE-derived effective angular momentum functions due to uncertainties of the degree-1 Stokes coefficients, C_{20} and GIA models.*

	Oceanic mass		Hydrological mass		Antarctica mass	
	χ_1^O	χ_2^O	χ_1^H	χ_2^H	χ_1^A	χ_2^A
	σ /RSD	σ /RSD	σ /RSD	σ /RSD	σ /RSD	σ /RSD
C_{10}, C_{11}, S_{11}	2.1 / 5	5.2 / 24	2.4 / 20	3.9 / 23	0.1 / 2	0.4 / 7
C_{20}	0.2 / 0.4	0.02 / 0.1	0.2 / 1	0.2 / 1	0.02 / 1	0.1 / 2
GIA	1.5 / 3	5.7 / 27	0.1 / 1	0.7 / 4	0.1 / 3	0.2 / 3

The C_{20} Stokes coefficient biases especially the mass estimates in the high latitudes and near the equator (30%), whereas the estimates in mid-latitudes are hardly affected; see Figure 1.17. Due to the fact that mass changes in the mid-latitudes have the largest influence on polar motion, the scatter of the C_{20} solutions has almost no impact on the hydrological and oceanic mass effects (1%) and about 0.1 mas (2%) on the Antarctic mass effect.

The uncertainties of the GIA models affect mainly mass estimates in Canada (50%), West Antarctica (50%) and in the North Atlantic (30%); see Figure 1.17. Thus, estimates of the χ_2 components are influenced significantly stronger than estimates of the χ_1 components. The scatter of the GIA models has the largest impact on the oceanic mass effect (about 5.7 mas; 27%), while the uncertainty for the hydrological mass effect amounts to only 0.7 mas (4%). For the Antarctic mass effect it amounts to 0.2 mas (3%).



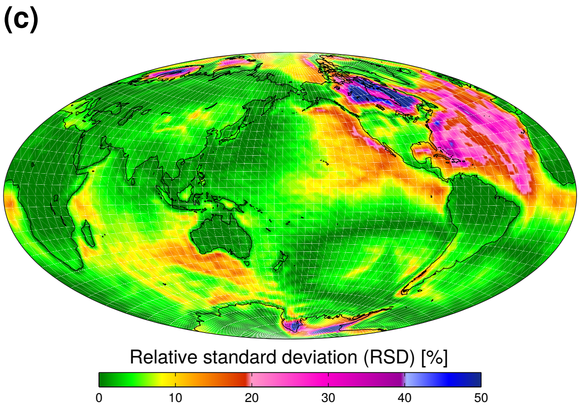


Fig. 1.17: *Relative standard deviation (RSD) of the GRACE-derived equivalent water heights due to (a) the omission of the degree-1 Stokes coefficients, (b) inaccurate C_{20} Stokes coefficients from GRACE and (3) the omission of the reduction of the GIA effect.*

Vertical reference systems

One main objective of the Global Geodetic Observing System (GGOS) is the implementation of the International Height Reference System (IHRS) as stated in the Resolution No. 1 of the International Association of Geodesy (IAG) released in July 2015, see Ihde et al. (2017). DGFI-TUM supports this initiative by coordinating the GGOS Focus Area Unified Height System and the Working Group “Strategy for the Realization of the IHRS” (see ihrs.dgfi.tum.de). These activities count on the concurrence of the International Gravity Field Service (IGFS), the IAG Commissions 1 (Reference Frames) and 2 (Gravity Field), the IAG Inter-commission Committee on Theory (ICCT), the IAG Regional sub-commissions for reference frames and geoid modelling, and both GGOS Bureaus: Networks and Observations (BNO) and Products and Standards (BPS).

At present, the main challenges are the establishment of the International Height Reference Frame (IHRF); i.e. a global reference network with precise geopotential numbers referring to the IHRS; and the preparation of required standards, conventions and procedures to ensure consistency between the definition (IHRS) and the realization (IHRF); i.e., an equivalent documentation to the IERS conventions is needed for the IHRS/IHRF. Figure 1.18 shows the station selection for the first IHRF realization. This network was designed on a preliminary proposal made by DGFI-TUM. It was distributed to regional and national experts to get advice about the availability of gravity data (or possibilities to survey them), and the addition of further geodetic sites to improve the density and distribution of the IHRF stations in their regions/countries. Based on this network, next efforts concentrate on the computation of the station potential values and the assessment of their accuracy. Additional efforts concentrate on designing a suitable strategy for the integration of the existing height systems to the global IHRS/IHRF as shown in Sánchez and Sideris (2017).

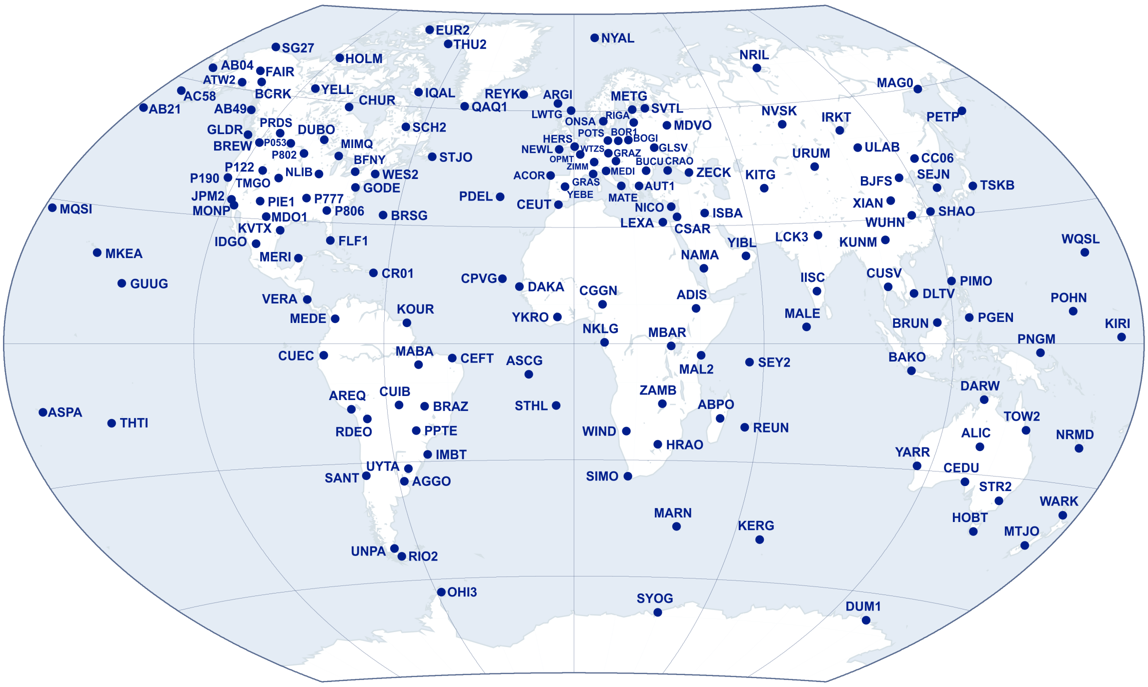


Fig. 1.18: *First proposal for the International Height Reference Frame (IHRF) station network.*

Related publications

Bloßfeld M., Angermann D., Seitz M.: ITRS Combination Centres: Deutsches Geodätisches Forschungsinstitut (DGFI-TUM). In: Dick W.R., Thaller D. (Eds.), IERS Annual Report 2016, 2017

Bloßfeld M., Rudenko S., Kehm A., Panafidina N., Müller H., Angermann D., Hugentobler U., Seitz M.: Consistent estimation of geodetic parameters from SLR satellite constellation measurements. Journal of Geodesy, in press, 2018

Ihde J., Sánchez L., Barzaghi R., Drewes H., Foerste Ch., Gruber T., Liebsch G., Marti U., Pail R., Sideris M.: Definition and proposed realization of the International Height Reference System (IHRS). Surveys in Geophysics, 38(3), 549–570, doi:10.1007/s10712-017-9409-3, 2017

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Kwak Y., Gerstl M., Bloßfeld M., Angermann D., Schmid R., Seitz M.: DOGS-RI: new VLBI analysis software at DGFI-TUM. Proceedings of the 23rd EVGA Meeting, Gothenburg, Sweden, 2017

Kwak Y., Bloßfeld M., Schmid R., Angermann d., Gerstl M., Seitz M.: Consistent realization of celestial and terrestrial reference frames. Journal of Geodesy, doi:10.1007/s00190-018-1130-6, 2018

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Sánchez L.: SIRGAS Regional Network Associate Analysis Centre, Technical Report 2016. In: Villiger A., Dach R. (eds.), International GNSS Service Technical Report 2016 (IGS Annual Report), 105–114, doi:10.7892/boris.99278, 2017

Sánchez L., Sideris M.G.: Vertical datum unification for the International Height Reference System (IHRS). Geophysical Journal International, 209(2), 570–586, doi:10.1093/gji/ggx025, 2017

Seitz M., Bloßfeld M., Angermann D., Schmid R., Gerstl M., Seitz F.: The new DGFI-TUM realization of the ITRS: DTRF2014 (data). Deutsches Geodätisches Forschungsinstitut, Munich, doi:10.1594/PANGAEA.864046, 2016

2 Research Area Satellite Altimetry

The determination of water level changes via satellite altimetry has been a primary research goal of DGFI-TUM for many years. DGFI-TUM determines, monitors, and investigates the water level of the open ocean, in coastal areas, in sea ice regions, and of inland water bodies, such as lakes, rivers, and wetlands. The institute's data base comprehends the complete observation record of all altimetry missions that have been launched until now. After harmonization, consistent preprocessing, and relative calibration (multi-mission analysis; Section 2.1), these data are available for the joint analysis and for the investigation of various phenomena in the ocean and the continental hydrosphere. The research is focused on the determination of most accurate water levels using advanced analysis methods. This is the basis for various ocean and coastal applications (Section 2.2) and also for inland water level monitoring of lakes, rivers, reservoirs, and wetlands (Section 2.3). The institute operates an open database for satellite altimeter observations and derived high-level products (OpenADB). All data sets are provided to registered users free of charge.

2.1 Multi-Mission Analysis

Upgrade of OpenADB website

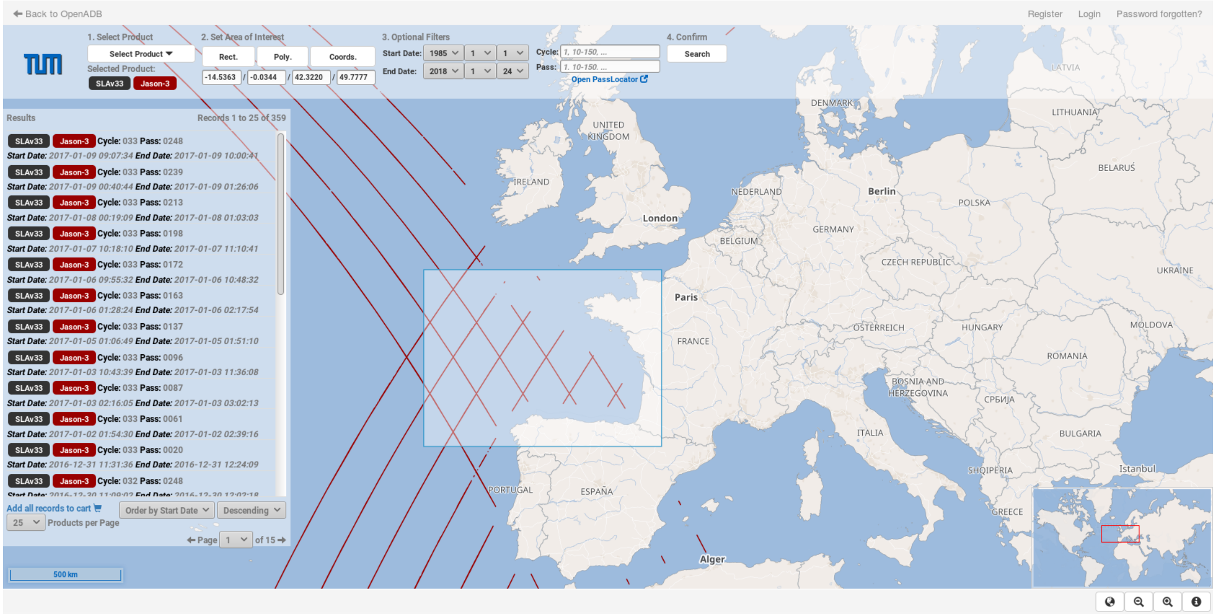
DGFI-TUM operates the Open Altimeter Database (OpenADB), which provides satellite altimeter observations and derived high-level products. All products are carefully harmonized and cross-calibrated in order to allow long-term multi-mission applications. The data holding is continuously updated by adding new missions (e.g., Sentinel-3A), orbit products (e.g., based on GDR-E orbit standards) and models (e.g., DTU15 mean sea surface).

Currently, OpenADB offers the following data sets:

- Sea Surface Heights (SLA)
- Sea Level Anomalies (SLA)
- Instantaneous Dynamic Ocean Topography (iDOT)
- ALES Sea Surface Heights (SSH_ALES)
- Empirical Ocean Tide Model (EOT)
- Vertical Total Electron Content (VTEC)

In 2017, a major upgrade of the OpenADB website has been performed. First, the corporate design of the TUM has been implemented, and second, the internal product management has been improved. This allows users to take advantage of a new graphical data extraction tool (Fig. 2.1) for the data selection, which became more user-friendly. Users obtain direct information about the data availability of their products of interest. Moreover, user-defined requests related to specific passes, cycles and areas can be handled. The data access of OpenADB is free for everyone after a short registration process on http://openadb.dgfi.tum.de.

Finally, the pass locator of OpenADB has also been improved: In addition to nominal satellite tracks, it also shows all 1Hz measurements and detailed information (e.g. pass number). Next to conventional OpenADB products, a new global mean sea level time series (01/1993 – 02/2017, Trend: 3.09 mm/y) has been computed and can be downloaded. Finally, a detailed overview of all satellite altimeter missions and corresponding detailed information such as satellite parameters, orbits, etc. is available in the mission section on the OpenADB website.



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Records 1 to 25 of 359

SLAv33 Jason-3 Cycle: 033 Pass: 0248
Start Date: 2017-01-09 09:07:34 End Date: 2017-01-09 10:00:41
SLAv33 Jason-3 Cycle: 033 Pass: 0239
Start Date: 2017-01-09 00:40:44 End Date: 2017-01-09 01:26:06
SLAv33 Jason-3 Cycle: 033 Pass: 0213
Start Date: 2017-01-08 00:19:09 End Date: 2017-01-08 01:03:03
SLAv33 Jason-3 Cycle: 033 Pass: 0198
Start Date: 2017-01-07 10:18:10 End Date: 2017-01-07 11:10:41
SLAv33 Jason-3 Cycle: 033 Pass: 0172
Start Date: 2017-01-06 09:55:32 End Date: 2017-01-06 10:48:32
SLAv33 Jason-3 Cycle: 033 Pass: 0163
Start Date: 2017-01-06 01:28:24 End Date: 2017-01-06 02:17:54
SLAv33 Jason-3 Cycle: 033 Pass: 0137
Start Date: 2017-01-05 01:06:49 End Date: 2017-01-05 01:51:10
SLAv33 Jason-3 Cycle: 033 Pass: 0096
Start Date: 2017-01-03 10:43:39 End Date: 2017-01-03 11:36:08
SLAv33 Jason-3 Cycle: 033 Pass: 0087
Start Date: 2017-01-03 02:16:05 End Date: 2017-01-03 03:02:13
SLAv33 Jason-3 Cycle: 033 Pass: 0061
Start Date: 2017-01-02 01:54:30 End Date: 2017-01-02 02:39:16
SLAv33 Jason-3 Cycle: 033 Pass: 0020
Start Date: 2016-12-31 11:31:36 End Date: 2016-12-31 12:24:09
SLAv33 Jason-3 Cycle: 032 Pass: 0248
Start Date: 2016-12-30 11:09:02 End Date: 2016-12-30 12:02:18

Order by Start Date: Descending

25 Products per Page

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Fig. 2.1: *New graphical data extraction tool of the OpenADB website (openadb.dgfi.tum.de/en/data_access).*

Assessment of Sentinel-3A orbit quality

The multi-mission crossover analysis (MMXO) tool that is used for the relative calibration of all altimetry missions also provides valuable information on the quality and consistency of orbit products of single missions. In the frame of the Copernicus Precise Orbit Determination Quality Working Group (POD QWG) the quality of different Sentinel-3A (S3A) orbit products has been checked. S3A sea surface heights (SSH) are computed based on and S3A non-time-critical (NTC) L2 observation data between June 2016 and January 2017 and eight different orbit solutions (seven from individual analysis centers and one combined solution). These SSH are used to build crossover differences and to estimate radial errors relative to Jason-3. Within this process data from Jason-2, Cryosat-2, and SARAL is used in order to establish a comprehensive and well distributed data base.

When building and analysing single-satellite SSH crossover differences (SXO) with a maximum time difference of two days, only small performance differences between the different orbit solutions are visible. Best performance is reached using the orbit of TU Delft (TUD) that yields mean SXO differences of about 2 mm and mean standard deviations below 4.9 cm (Fig. 2.2).

When analyzing the radial errors computed by the MMXO, one can identify two groups of orbits (AIUB/DLR/TUD/TUM and CNES/ESOC/CPOD) between which the mean of radial errors differ by about 7 mm. The geographically correlated mean errors (GCE) show almost not differences between six of the solutions with values up to about 2 cm. Here, only the TUM solution shows a different pattern (z-shift with respect to the other orbit solutions).

From these analysis one can conclude that the overall quality of S3A orbit products is good with only small differences between the different solutions. All analysis results are summarized in Tab. 2.1 More details can be found in Dettmering (2017)[1].

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[1] Dettmering D.: Multi-mission crossover analysis at DGFI-TUM. presented at Copernicus POD Quality Working Group Meeting, Darmstadt, Germany, 2017-05-09

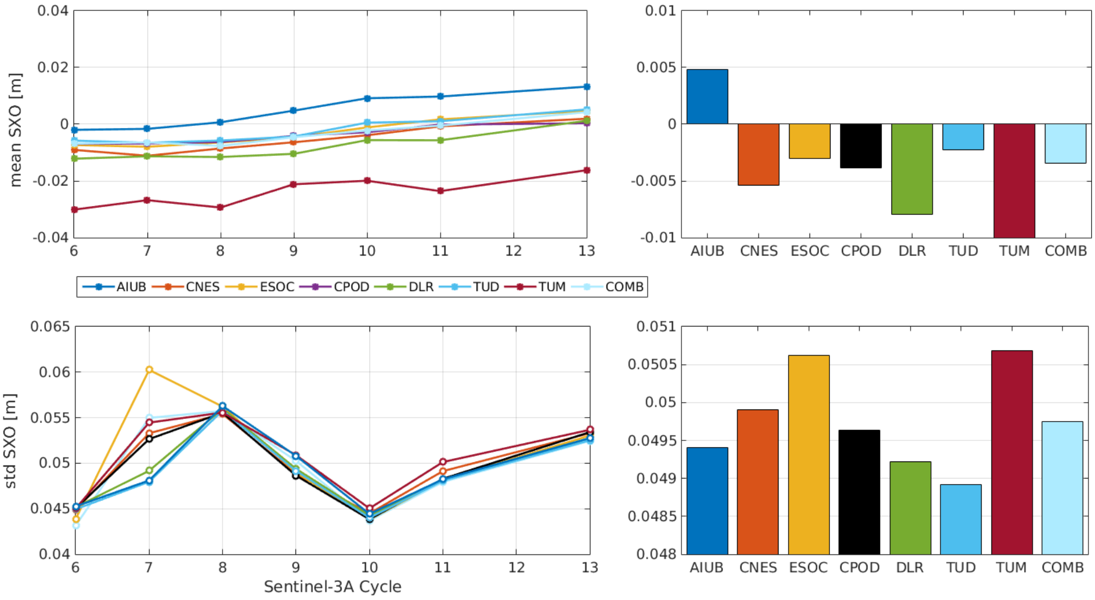

Fig. 2.2: *Single-satellite SSH crossover differences (means (top) and standard deviations (bottom)) with a time limit of 2 days; per cycle (left) and global means(right).*

Table 2.1: *Summary of all analysis results from MMXO for eight different S3A orbit solutions (all numbers in mm)*

	radial errors			$\Delta\delta$		GCE		dz wrt J3	
	mean	std	ampl. Rev.	mean	std	mean	std	mean	std
AIUB	44.7	14.9	5.6	1.7	4.1	−0.6	5.2	−5.0	3.8
CNES	38.8	14.3	8.9	−2.0	4.4	−0.5	4.5	−6.0	3.6
ESOC	38.5	15.6	7.6	−0.9	4.3	−0.3	5.1	−7.4	3.6
CPOD	39.0	14.7	7.1	−1.2	4.2	−0.5	5.1	−7.3	3.3
DLR	45.2	16.6	13.5	−2.8	4.6	−0.7	5.2	−6.0	3.2
TUD	44.3	14.8	5.3	−0.7	4.2	−0.8	5.3	−7.0	3.5
TUM	44.6	18.2	89.2	−8.8	6.1	−1.5	5.6	0.1	6.2
COMB	42.6	14.6	6.4	−1.4	4.2	−0.8	5.0	−6.0	3.5

2.2 Sea Surface

Exploitation of the ALES dataset

During 2017 the data based on the ALES algorithm, which was initially designed as an attempt to improve the quality of radar altimetry information in the coastal zone, made several steps forwards in mainly two directions: the exploitation of the dataset as a general ocean retracker without the need to distinguish between coastal zone and open-ocean, and the transition to a more user-friendly format.

The dataset was expanded in length, since the algorithm was applied and validated to the ERS-2 period (1996–2002)[2]. Moreover, a first version of a 1-Hz dataset was derived and made available to the public (via OpenADB; see Sect. 2.1). 1-Hz data are averages of sea level data every roughly 7 km and are usually preferred by oceanographers as a good compromise between noise and spatial resolution. An extensive validation of the open ocean data demonstrated that the ALES data outperform the current open ocean standards. The validation was

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[2] Passaro M., Calafat F. M.: ALES coastal processing applied to ERS: Extending the coastal sea level time series. 10th Coastal Altimetry Workshop, Florence, Italy, 2017-02-21

based on two techniques: on one side the single-mission crossover analysis, i.e. the comparison of sea level data taken approximately at the same location and close in time[3] (see Fig. 2.3), on the other side a detailed spectrum analysis based on the spatial frequencies, which highlighted how ALES data are currently the most effective in detecting the mesoscale structures of the ocean variation (20–80 km of spatial scale)[4].

A regional user-dedicated dataset were also published for the North Sea and the Mediterranean (COSTA dataset; Passaro, 2017). In this case, data were corrected and assembled in time and space in order to provide to the users a time series for each along-track satellite point.

Finally, we have used the ALES dataset in collaboration with other groups to perform a first experiment of coastal data assimilation with hydrodynamic models in the Black Sea[5] and to combine and compare data with in-situ measurements in the Southern Patagonia (Lago et al., 2017). The dissemination and exploitation of ALES is now at the focus of our efforts, as demonstrated by the relevance that the methodology and the results gained in Cipollini et al. (2017), the chapter of the new textbook of Satellite Altimetry that we co-authored.

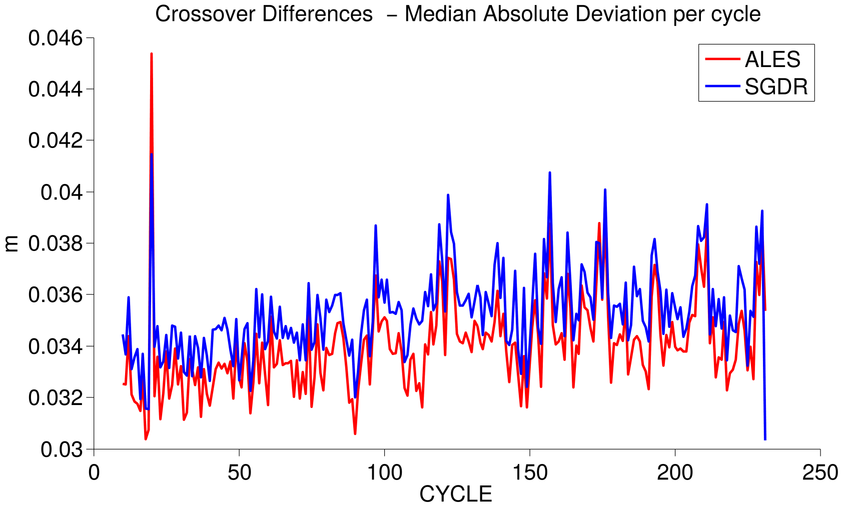

***Fig. 2.3:** Median Absolute Deviation of the difference of sea surface height at Jason-2 crossovers in the open ocean. The use of ALES compared to the standard product (SGDR) brings a 0.13 cm improvement, which corresponds to a 7.5% decrease of the variance of the differences.*

Arctic Ocean altimetry: the Sea Level Climate Change Initiative

Sea level retrieval at high latitudes is normally hampered by the presence of sea ice. In this case, sea level needs to be computed on leads, the openings among the ice-covered ocean. The European Space Agency (ESA) has fostered in recent years significant efforts to improve sea level at high latitudes. In this context, DGFI-TUM is part of the consortium of the Sea Level Climate Change Initiative (SL_cci). Our role was aimed at providing new experimental data in the Arctic of importance to climate research (Legeais et al., 2017).

The first part of the DGFI-TUM contribution was performed already during 2016. In this stage, a dedicated waveform fitting algorithm, called ALES+, was developed. The aim was to build a versatile algorithm that could deal with radar returns coming from different backscattering sources. The second half of the project, during 2017, was mainly dedicated to the tuning of the algorithm, the generation of a dataset, and the validation of the results. The ambitious objective

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[3] Passaro M., Smith W., Schwatke C., Piccioni G., Dettmering D.: Validation of a global dataset based on subwaveform retracking: improving the precision of pulse-limited satellite altimetry. OSTST Meeting 2017, Miami, USA, 2017

[4] Smith W.H.F., Leuliette E.W., Passaro M., Quartly G., Cipollini P.: Covariant errors in ocean retrackers evaluated using along-track cross-spectra. OSTST Meeting 2017, Miami, USA, 2017-10-23

[5] Bonaduce A., Passaro M., Storto A.: Impact of coastal altimetry data in the Black Sea physical ocean analysis system. 10th Coastal Altimetry Workshop, Florence, Italy, 2017-02-22

was to verify whether the heights estimated by a single algorithm could be used not only in the sea-ice covered ocean, but also in other challenging environments that present similar signal disturbances (coastal ocean and inland waters), as well as generally in the open ocean.

The tuning of the algorithm went also through visual checks of its ability to fit very different signals registered by the satellite. Figure 2.4 shows typical altimeter returns from the open ocean (leading edge with a decaying trailing edge), coastal ocean (leading edge with strong noise in the trailing edge) and leads or small lakes and rivers (peaky waveform). ALES+ is able to always fit the relevant part of the return, the leading edge, in which the reference point of the water surface is located (vertical black line in the figure).

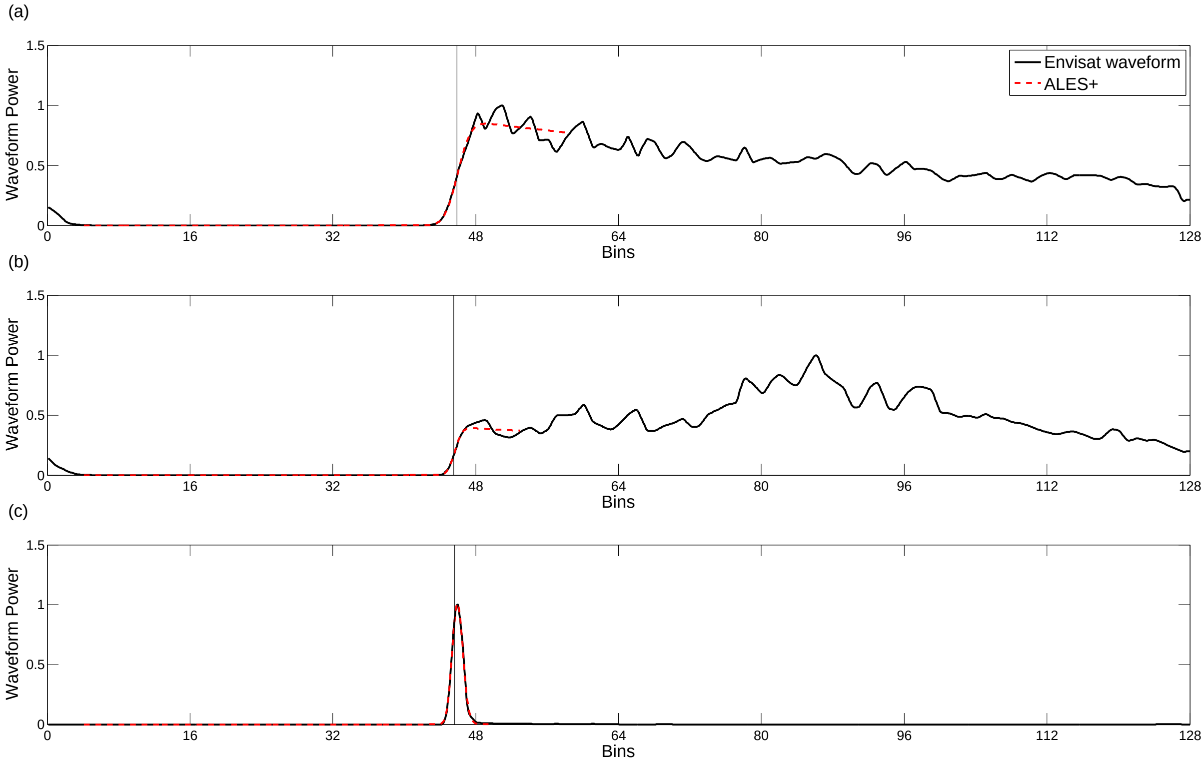

Fig. 2.4: *Examples of ALES+ waveform fitting for three different trailing edge slope conditions typical of open ocean (a), coast (b) and leads (c). A black vertical line highlights the location of the retracking point estimated by ALES+.*

The precision of the ALES+ estimations was tested by means of in-situ data and reference surfaces. Concerning the latter, the variation of the retrieved heights w.r.t. a geoid model independent from altimetry was tested in the Arctic Ocean and in the coastal ocean. While the difference between sea surface height and geoid also includes the sea level variability, a significant part is simply noise. Therefore, comparing different algorithm against each other, one can assess which method has the best noise performances. As seen in Table 2.2 for what concerns peaky waveforms (therefore returns associated with leads), ALES+ shows the best performances not only compared to the ocean retracker available in the standard product (SGDR-Ocean), but also to a retracker that was designed for this purpose (SGDR-Seaice). In the coastal zone (Figure 2.5), ALES+ improves the performances of the original product, which is visibly noisier in the last 5 km, and is close to the performances of ALES. This is expected, since ALES+ seeks a compromise in order to be able to re-

Table 2.2: *Median Absolute Deviation between GOCO5s geoid heights and SSH data retracked with ALES+, SGDR-Ocean and SGDR-Seaice retracker for peaky waveforms in the Svalbard test area.*

	ALES+	SGDR-Ocean	SGDR-Seaice
ERS-2	0.2620 m	0.3659 m	0.2901 m
Envisat	0.2142 m	0.2961 m	0.2364 m

trieve the sea level in the leads, while ALES usefulness is only limited to the open ocean and the coastal zone. A full description of the algorithm and validation was presented in Passaro et al. (2017)[6], and is going to be published in Passaro et al. (submitted).

This study will be a basis on which to build future research at DGFI-TUM to unveil the sea level dynamics in the Arctic and Antarctic Ocean and represents a step forward in the attempt to avoid biases and inconsistencies due to the use of different approaches in retrieving the sea level depending on the characteristics of the reflecting surface.

The project also saw the profitable collaboration with the Danish Technological Institute (DTU). This resulted in the assimilation of the ALES+ reprocessed dataset (concerning the years of ERS-2 and Envisat altimetry missions, i.e. 1996–2002) into a 25-year-long multimission sea level product that is made freely available on request together with the other products of SL_cci.

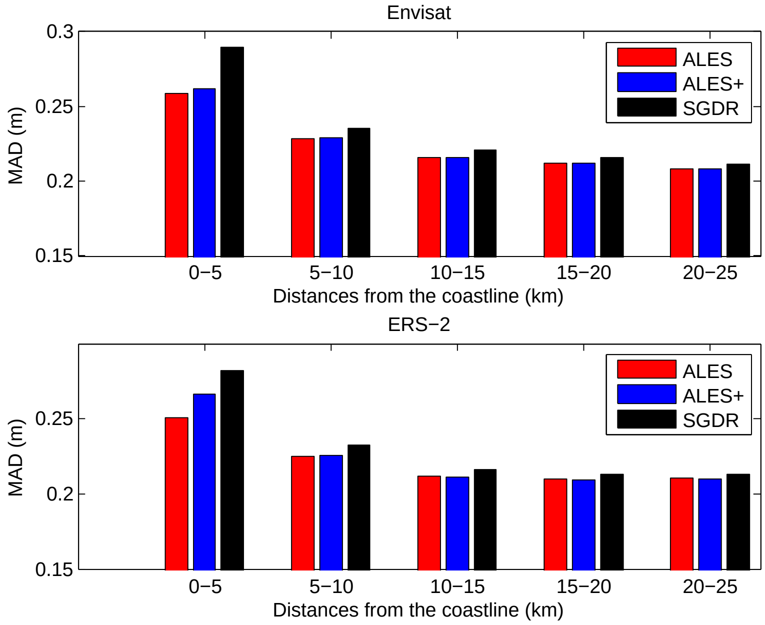

Fig. 2.5: *Median Absolute Deviation between GOCO5s geoid heights and SSH data retracked with ALES, ALES+ and SGDR in 5 km wide distance bands.*

Arctic Ocean altimetry: DFG project NEG-OCEAN

The Arctic Ocean and its peripheral seas, e.g. the Greenland Sea and the Fram Strait, located in the North-East of Greenland are considered one of the most important components of the Earth's climate system. Most of the Arctic cold and fresh water is carried through the Fram Strait and Greenland Sea southwards in the Atlantic ocean and plays a main contributor to the global ocean current system. Within the DFG-funded project NEG-OCEAN, DGFI-TUM investigates the impact of climate change on ocean variability in the North-East of Greenland by analyzing altimetry sea level observations of more than 20 years.

Most of the North polar regions are at least temporarily covered by sea-ice. This causes ice contamination of the altimetry radar pulses (waveforms) and hinders a reliable observation of sea surface heights by satellite altimetry. To extract reliable information about the sea surface a waveform classification is performed in order to separate open water observations registered over small water openings (e.g. leads, polynyas) from sea-ice observations. For this purpose DGFI-TUM developed an unsupervised classification approach (i.e. without any training data),

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[6] Passaro M., Rose S.K., Andersen O.B., Boergens E., Calafat F.M., Dettmering D., Benveniste J.: ALES+: Adapting a homogeneous ocean retracker for satellite altimetry to sea ice leads, coastal and inland waters. OSTST Meeting 2017, Miami, USA, 2017-10-23

which is based only on the waveforms' shapes. Briefly summarized, the unsupervised classification approach, described by Müller et al. (2017), groups an unassigned subset of altimetry radar waveforms into a predefined number of classes by applying a partitional cluster algorithm (i.e., K-medoids) in order to establish a waveform model of reference, to which different waveforms with specific surface characteristics are associated. In the following step, the generated waveform model acts as a kind of assignment map for the remaining waveforms, which are allocated to the particular classes using a simple K-nearest-neighbour classifier. This is done for each satellite mission, individually.

For validation, the classification results are compared to imaging SAR data. For this purpose, DGFI-TUM implemented an automatic image processing strategy (Passaro et al., 2017) enabling a segmentation of lead and polynya areas in order to directly compare the classified altimetry tracks to binary converted pixel values (i.e. water = 1, ice = 0). This has been done using 19 comparison pairs for the ESA satellite Envisat versus radar scenes from Radarsat-2 (MDA)/ALOS (JAXA/METI) and the CNES/ISRO altimetry mission SARAL versus image snapshots from Sentinel-1A (Copernicus), respectively. In total 15.025 Envisat and 19.919 SARAL classifications are available for the comparison, resulting in a consistency rate of 70.7% for Envisat and 76.9% for SARAL. More information regarding the assessment of the classification results can be found in Müller et al. (2017).

Figures 2.6 displays two examples from the Envisat classification in September 2004 (left) and December 2006 (right). The along-track altimetry data is assigned to four classes indicating ocean, lead/polynya, sea-ice and undefined surface conditions. In winter, the sea-ice cover reaches its maximum (red), however showing still some small open water areas (light blue, blue) within the sea-ice zone. In contrast, the summer is characterized by large open ocean areas with drifting sea-ice areas.

Summarizing all open water (ocean and leads/polynya) and sea-ice (including undefined) classifications an altimeter based sea-ice concentration (SIC) can be computed. Figure 2.7 displays the seasonal evolution of the SIC in percentage for the Greenland Sea and Fram Strait area during the Envisat period. The temporal evolution of the classification-based SIC (blue) is compared to sea-ice concentrations gathered by a combination of the Envisat on-board radiometer and altimeter (red) and a gridded external dataset provided by the National Snow and Ice Data Center (yellow) including passive microwave and in-situ observations. In general the seasonal sea-ice cycle is clearly visible. However, the SIC based on the unsupervised classification shows smaller values, which can be attributed to a higher spatial resolution of the along-track data than the passive radiometers resulting in a better detecting of small open water gaps within the sea ice.

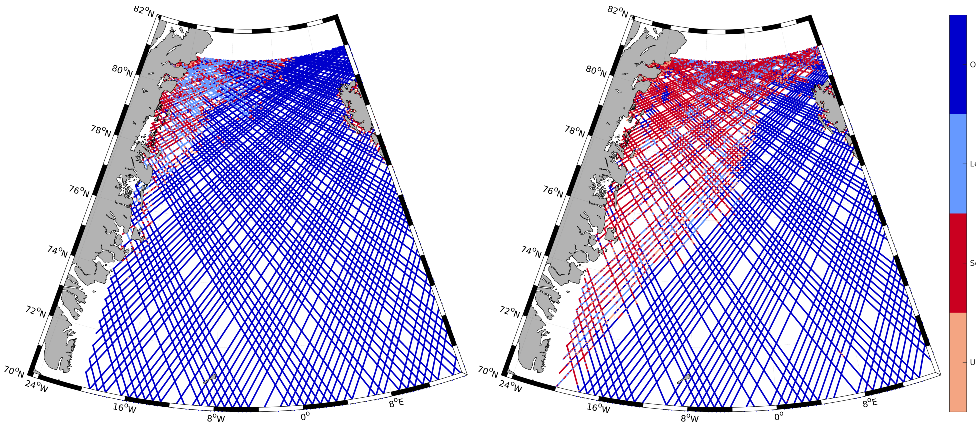

Fig. 2.6: *Envisat waveform classes for September 2004 (left) and December 2006 (right) highlighting different surface conditions in the Greenland Sea and Fram Strait.*

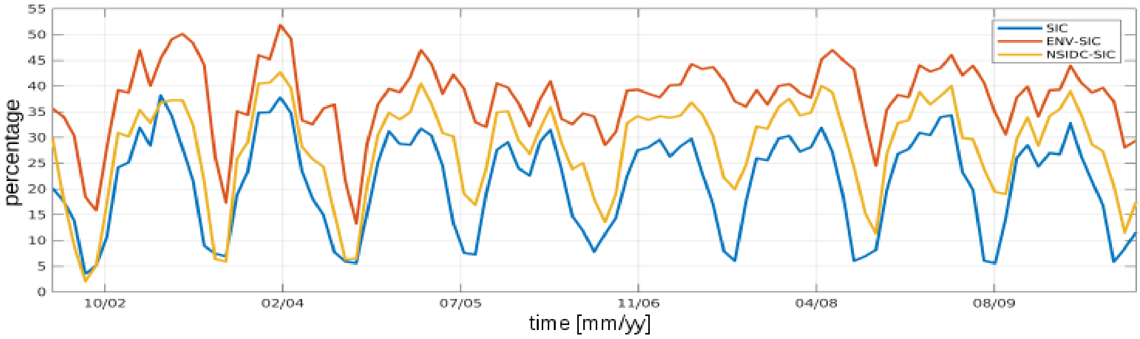

Fig. 2.7: *Temporal evolution of the sea-ice concentration (SIC) along the Envisat tracks: from Envisat waveform classification (in blue), from on-board Envisat sea-ice flag (in red), and from external sea-ice concentration based on gridded passive microwave and in-situ observations, provided by the National Snow and Ice Data Center (NSIDC) (in yellow).*

When using only altimetry observations classified as open water, reliable sea surface heights in the sea-ice covered regions of the North polar seas can be computed. Figure 2.8 shows a snapshot of the dynamic ocean topography in March 2008 (sea-ice maximum) derived from Envisat sea surface heights using the unsupervised classification approach, the ALES+ retracker, and the EIGEN6C4stat geoid model. One can clearly identify a lot of data gaps due to the flagging of sea-ice contaminated observations. Accordingly, almost no outliers are visible in the plot. In order to fill the gaps, it is planned to couple the altimetry observations with a high-resolution ocean model and to derive a reliable Arctic dynamic topography and geostrophic ocean currents.

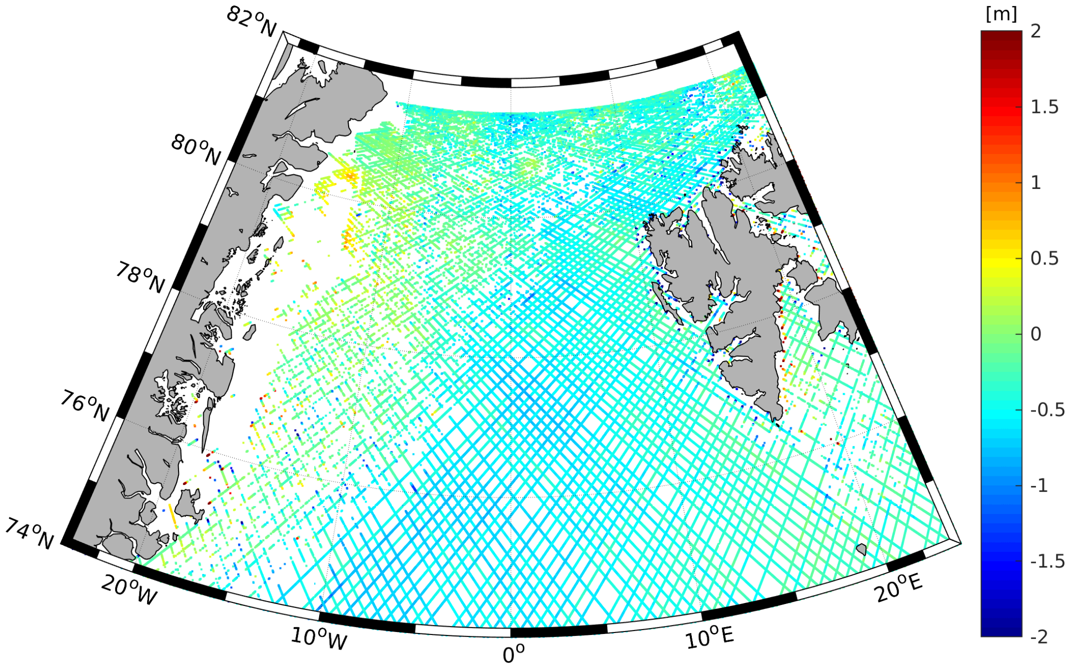

Fig. 2.8: *Envisat along-track sampled dynamic ocean topography observations in March 2008*

Impact of ALES retracking on coastal tide estimation

During the last decades improvements in ocean tide models were observed for deep-ocean and shallow-water areas. However, difficulties are still found in the characterization of the harmonic constituents for coastal regions. Because of complex tidal regimes or a poor data distribution, in these zones tide models show not only a reduced performance, but also larger disagreement among the models themselves. For these reasons, part of the DGFI-TUM project for the update of Empirical Ocean Tide (EOT) model is focused on these specific areas.

In 2017 studies were dedicated to understand the impact of the ALES retracker on the performance of a tide model. ALES is a retracker tailored for coastal areas, which provides a larger amount of data with high reliability with respect to an ordinary technique. The experiment was made using high-rate observations from Jason-1 and Jason-2 missions, covering a continuous period of 14 years, from January 2002 until February 2016. The data were extracted from the DGFI-TUM's Open Altimeter Database (OpenADB). The approach applied to compute the tidal constituents is similar to the approach used for computation former versions of the EOT model: residual tidal constituents are derived on a least-squares-based harmonic analysis applied to Sea Level Anomalies (SLA) which are corrected for the FES tide model. In order to assess the impact of a coastal retracker, the model is once derived with ALES, and once estimated with an ordinary retracker, which is the original SGDR product available on our database. The results are then compared against tide-gauge records according to the classical statistical terms, such as the root-mean square differences (ΔRMS) for single tidal constituents. It was chosen to compute the solutions along-track, as it was possible to study the evolution of the model and the impact of the retrackers while approaching the coast. Nodes on each track with a distance of 7 km were used to derive the model. The tracks were selected according to their distance to valid tide gauge measurements, and avoiding sites close to rivers, so that non-tidal signals could be detected. The tidal constituents estimated in this work are: M_2, S_2, N_2, K_2, K_1, Q_1, O_1, and P_1.

In Fig. 2.9 one can observe the difference in the RMS between the model obtained with the SGDR retracker and the one provided by ALES for the single constituents, plotted against the longitude of the location of the closest node to the tide gauge. In this way it is possible to see the improvements at the single sites, and for all the constituents. The plot is divided in three rows for an easier visualization. The results show that ALES retracker offers an improvement for most of the stations analysed. Particularly interesting are the results at longitudes -14.55, 113.96, 23.36, and 25.34 (respectively stations at Cape Bojador, South China Sea, and two in the Baltic Sea), for which most of the constituents are improved with the ALES solution. Another station worth to mention is the one located at longitude -2.65 (in the Firth of Forth), where constituent M_2 shows an improvement larger than 5 cm. An overall result can be seen in Tab. 2.3, where the average RMS at the closest nodes was computed for each constituent. The ALES solution offers a general improvement in comparison with the SGDR results. In certain cases the differences (third column) are larger than 0.5 cm, which represent a remarkable impact for a retracker on a tide model. From the relative differences (ΔRMS [%]), it can be noticed that major improvements mainly occur for smaller constituents.

Table 2.3: *Average of RMS for major constituents for the closest points to the tide gauges. The values are expressed in cm. The last column shows the number of the tide gauges used to compute each average.*

Constituents	RMS_{ALES} [cm]	RMS_{SGDR} [cm]	Δ RMS [cm]	Δ RMS [%]	n° stations
M2	11.71	11.94	0.23	1.94	41
N2	3.55	3.59	0.03	0.89	41
S2	5.10	5.47	0.37	6.81	41
K2	1.71	2.34	0.63	27.04	39
K1	2.95	3.29	0.34	10.31	41
O1	1.89	2.53	0.64	25.23	41
Q1	1.00	1.48	0.48	32.19	29
P1	1.48	1.93	0.45	23.12	41

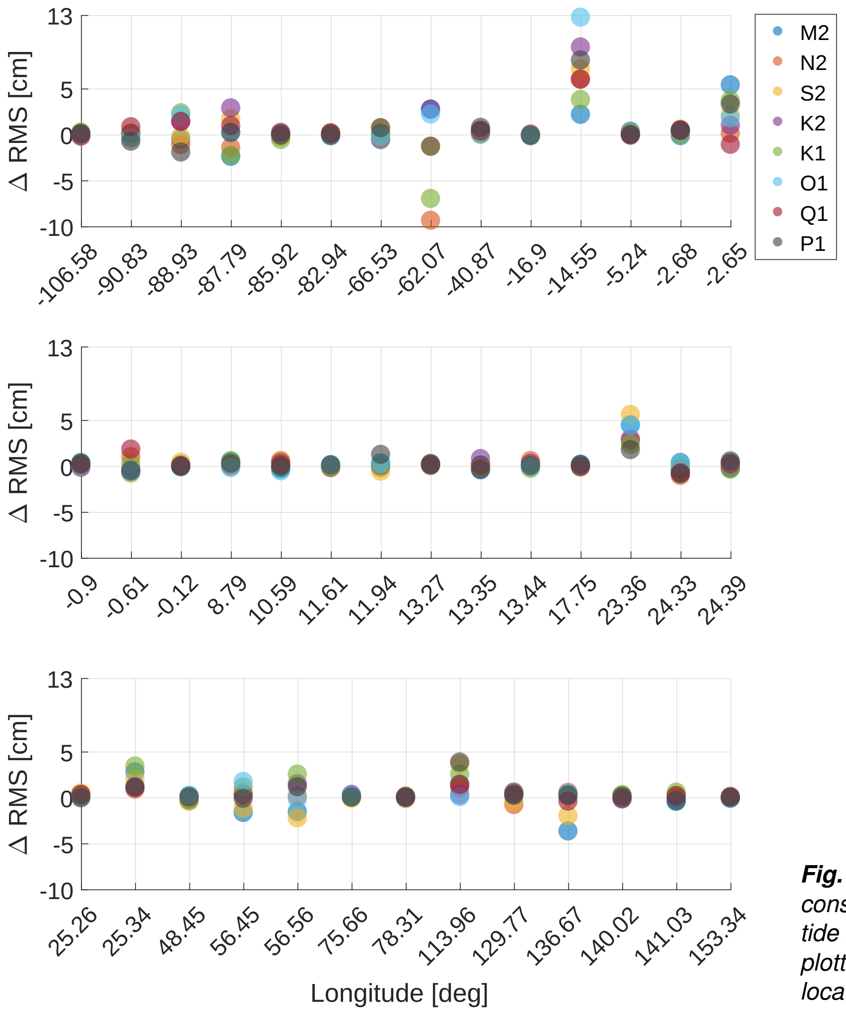

Fig. 2.9: *Difference of RMS for major constituents at the closest node to the tide gauge of interest. The values are plotted against the longitude of their location.*

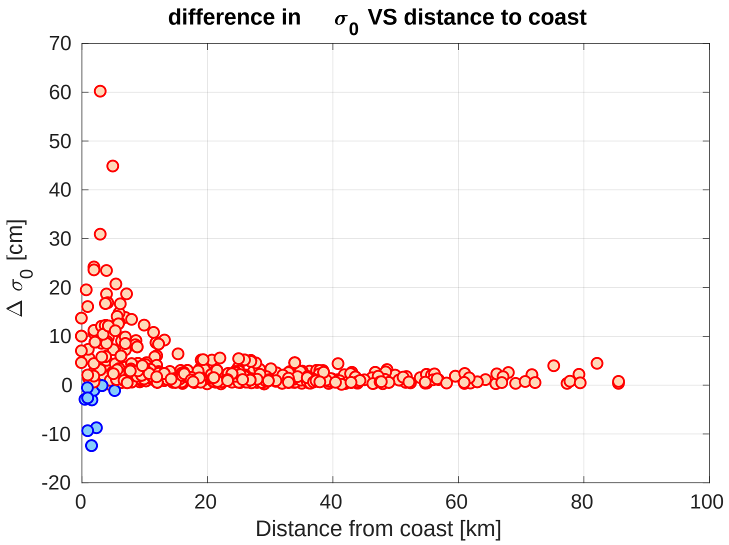

Fig. 2.10: *Difference of σ_0 at each node against the distance to coast. The blue dots show the cases for which the ALES solution has a large internal error, and the red dots correspond to a smaller σ_0 for ALES.*

Another interesting comparison was done for the variable σ_0, plotted against the distance to the nearest coast. σ_0 represents the quality of the least squares fit, i.e. the internal error of the model. Fig. 2.10 shows the difference at each node between the σ_0 computed for the SGDR solutions and the ones obtained from ALES ($\Delta\sigma_0$). A positive value on the y-axis (red dots) corresponds to a larger fitting error for the SGDR solutions, negative values (blue dots) for the contrary. From the plot it is clear that in most cases an improvement for σ_0 is achieved with ALES solutions with larger extent close to the shore. Small exceptions are found for few coastal points. The smaller errors for the ALES solution can be explained by two points: first, the increased number of observations, and second, the improved quality of the ALES ranges.

In the future, these studies will be extended to other minor tidal constituents, as well as other geophysical corrections, with the purpose of quantifying the impact of different altimetric components on the coastal tidal description. A gridded tide model version will also be developed, aiming to integrate additional missions such as ERS-2 and ENVISAT.

Interactions of the radar signal with waves and wind

The radar signal retrieved by an altimeter needs to be corrected for several factors, before it can be used to study sea level. Among the very important corrections is the Sea State Bias (SSB). It is usually empirically derived by studying the height differences at crossover points. The SSB is heavily dependent on wind and waves conditions, two variables that are also estimated by the altimeter (see Fig. 2.11). In this framework, we assessed the positive impact of a new SSB correction based on the wind and wave height output of ALES algorithm.

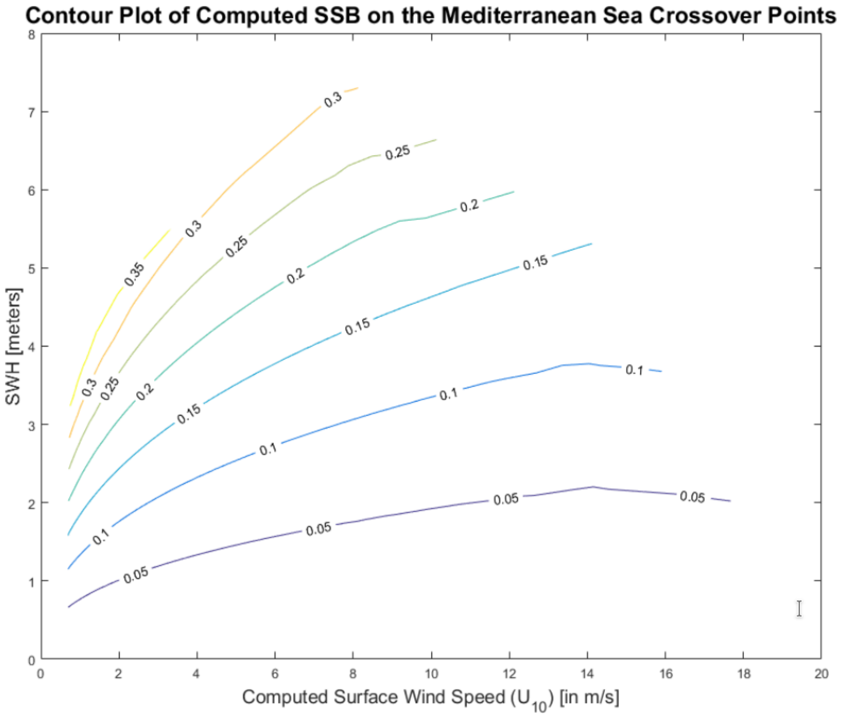

Fig. 2.11: Sea State Bias correction: regional model for the Mediterranean Sea computed using ALES estimations of wave height and wind. It can be seen how the value of the correction (m) increases with the sea state.

In the context of a Master Thesis (Nadzir, 2017), we have performed a first assessment of a regional SSB correction derived for the North Sea and the Mediterranean Sea. The conclusions of the study point out to two main findings:

1. Part of the sea state bias works as a correction of numerical errors related to the estimation process of sea level height together with waves and wind, rather than as an estimation of physical interaction between the radar signal and the waves.
2. An empirical model restricted to a region can improve the performances of a global model.

These conclusions will foster further research in the next years, in particular to understand whether an SSB correction developed only for shallow waters, where standard processing cannot correctly retrieve the ocean signal and where the physics of the waves significantly differ from the open ocean, could further improve the accuracy with which we can determine the coastal sea level.

2.3 Inland Altimetry

CryoSat-2 SAR data over rivers: a classification approach

Rivers are often only observed by very few consecutive altimeter measurements in one overflight of the river. These measurements have to be found in order to derive reliable water levels. However, the identification of water observations is challenging as land-water masks are often not accurate enough, especially to map small rivers. To this end, we developed a classification method for CryoSat-2 SAR data to identify the water observations solely based on the returned radar echoes and to estimate reliable water levels in the Mekong River Basin (Boergens et al., 2017b).

CryoSat-2 was launched in 2010 and is the first altimeter satellite carrying a Delay-Doppler or Synthetic Aperture Radar (SAR) altimeter. The advantage of SAR altimetry is the smaller along-track footprint compared to the conventional pulse limited altimetry. This increases the amount of measurements per overflight and the quality of derived water levels, especially for small rivers. CryoSat-2 has a long-repeat orbit with a repeat time of 369 days, which leads to a high spatial coverage with an observations every 7 km along the river.

The classification method used is a k-means clustering method based on features derived from the SAR multi-look waveforms and the Range Integrated Power (RIP) waveforms.

The non-uniform topography of the Mekong Basin requires to separately classify three different topographic regions: (I) Upstream, with small or medium sized rivers (smaller than 200 m) surrounded by hilly or mountainous regions; (II) middle stream, with medium sized rivers (smaller than 500 m) and a gentle landscape; and (III) downstream, where the river is surrounded by seasonal wetlands. For the downstream region the method fails as the classification is unable to discriminate between river and wetlands. In the other two regions, the classification results are used to estimate water levels at every crossing of the satellite track with a river in the basin. The classification approach works best for the upstream region with its small rivers. Even rivers as small as 20 m could be identified and observed with this method. Some rivers are identified that are too small to be included in an official land-water mask. Figure 2.12 shows the classification results and the derived water levels of one pass. The resulting water level heights for the whole basin are shown in Figure 2.13. In total, more than 2000 water levels are derived in the entire basin.

Observing and forecasting water level extremes in the Mekong River Basin with multi-mission altimetry

Single-mission altimetric water level observations of rivers are limited spatially and temporally and are thus often not able to observe the full extent of extreme flooding events. However, the spatial and temporal distribution of water level observations of all available altimetry missions is denser and more sufficient for the observation of floods. To get a multi-mission time series, the different altimetric observations have to be combined along the river. To this end, we employ an universal kriging (UK) approach with an appropriate covariance modelling.

Unlike the widely used ordinary kriging (OK), which was also used in previous works of our institute[7], UK allows for a non-constant mean in the data set. In the case of multi-mission altimetry, this implies that the mean water level or topography along the river does not need reducing in the altimetry observations beforehand. Therefore, we are able to incorporate the

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[7] Boergens E., Dettmering D., Schwatke C., Seitz F.: Treating the hooking effect in satellite altimetry data: a case study along the Mekong River and its tributaries. Remote Sensing, 8(2),91, doi:10.3390/rs8020091, 2016

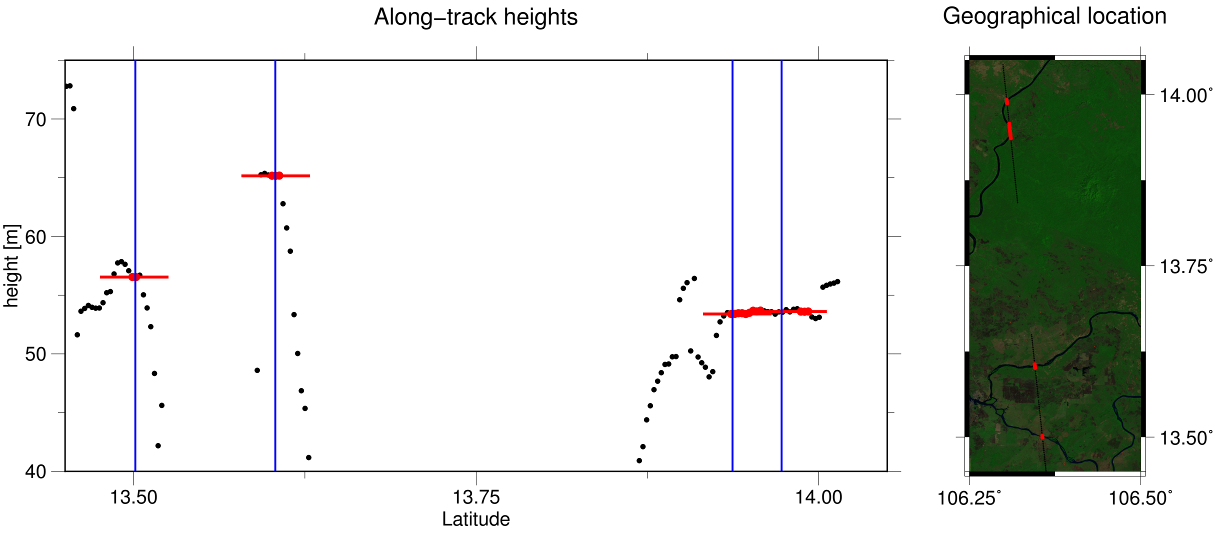

Fig. 2.12: *Heights along one CryoSat-2 track which crosses the river at four locations. The map on the right side shows the geographical surroundings with the background as a Landsat-8 scene where the rivers are well visible. The black dots are all retracked heights with the red dots indicating which measurements were classified as water. The blue vertical lines show the location of the crossing of the track with a river polygon and the horizontal lines are the estimated water level at each crossing.*

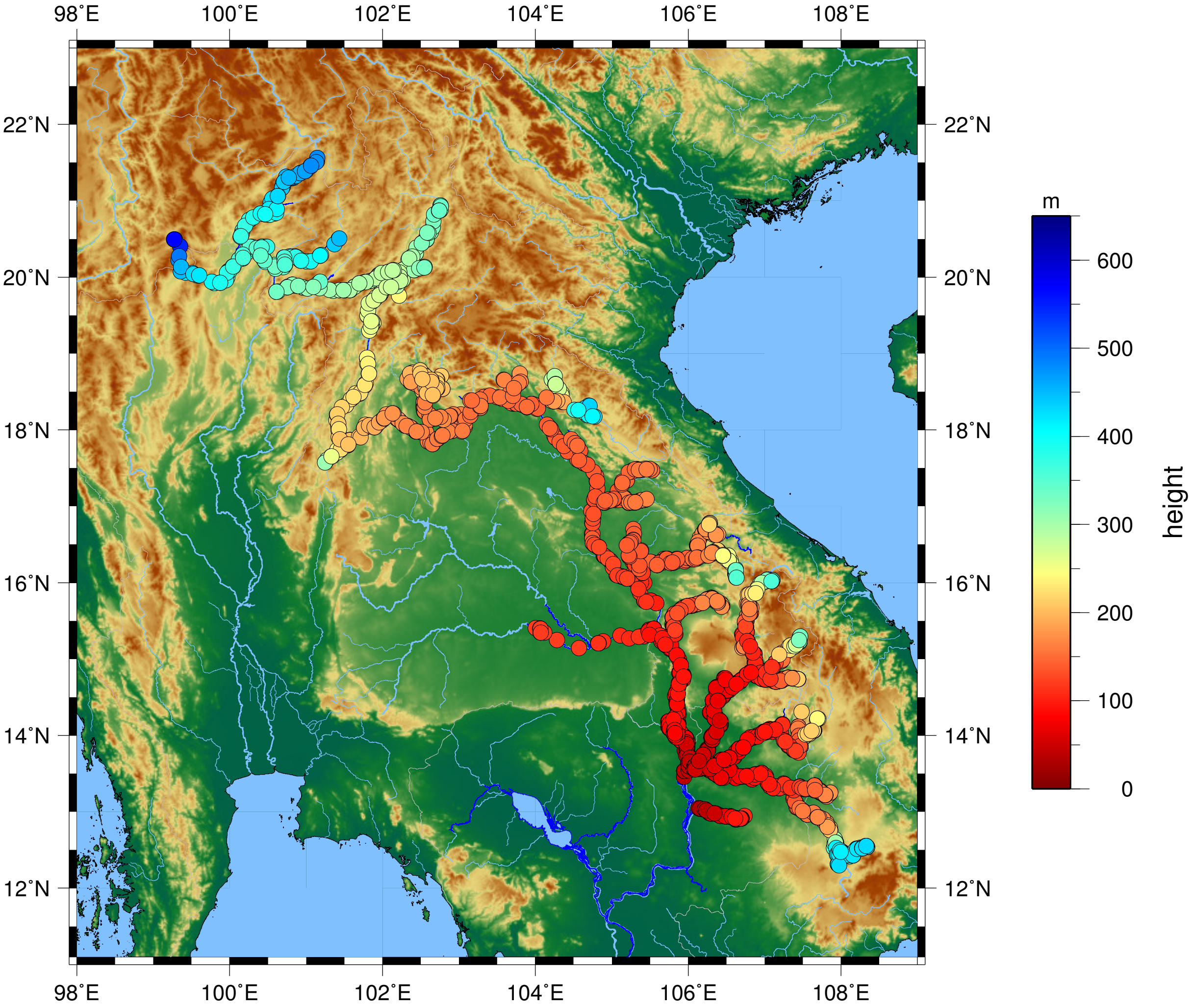

Fig. 2.13: *All derived CryoSat-2 water levels in the Mekong River Basin.*

data of long- or non-repeat orbit missions (LRO or NRO), most importantly CryoSat-2, in the multi-mission approach. The data of Cryosat-2 is important for the multi-mission approach along rivers as the data significantly densify the data coverage, especially spatially. While the mean water level of virtual stations (VS) of the short-repeat orbit missions (such as Envisat, SARAL, and Jason-2) can be derived directly from the long term mean of the time series, this is not possible for the long- or non-repeat missions. A reduction of the mean water level by topography models is usually not feasible due to the inaccuracy of these models.

In the UK approach, the unknown mean in the data is modelled with an unknown linear combination of known functions $\{f_0(\boldsymbol{x})...f_m(\boldsymbol{x})\}$. The water level $Z(\boldsymbol{s},t)$ observed at location $\boldsymbol{s}$ and at time t can then be written as

$$Z(\boldsymbol{s},t) \;=\; \sum_{j=0}^{m} f_j(\boldsymbol{s})\beta_j + \delta(\boldsymbol{s},t). \tag{2.1}$$

$\delta(\boldsymbol{s},t)$ is the water level variation at the given location w.r.t. the mean water level $\sum_{j=0}^{m} f_j \boldsymbol{s} \beta_j$ with the unknown parameter β_j. We choose polynomial B-Splines with spline order 2 for $f_j(\boldsymbol{s})$. m is the number of used B-Splines.

The universal kriging equation for the interpolation of a water level at point $\boldsymbol{s}_0$ and time t_0 is

$$p(\boldsymbol{s}_0,t_0) \;=\; \sum_{i=1}^{n} \lambda_i Z(\boldsymbol{s}_i,t_i), \tag{2.2}$$

with all altimetric water level observations $Z(\boldsymbol{s}_i,t_i)$ at the locations $\boldsymbol{s}_i$ and time t_i and

$$\boldsymbol{\lambda} \;=\; (\lambda_1,\ldots,\lambda_n) \;=\; (\Sigma_U + \Sigma_{alti})^{-1}\,\boldsymbol{c}_U. \tag{2.3}$$

$\boldsymbol{c}_U$ and Σ_U contain the covariances of all observations w.r.t. the interpolation point and the covariances among all observations. They are derived from a non-stationary covariance model described in Boergens et al. (2017a). This covariance model allows to incorporate observation data along tributaries as well in order to densify the data set.

For the multi-mission time series, we combine altimetry data between 2008 and 2016 registered by the short-repeat orbit missions Envisat, SARAL, Jason-2, Jason-2 EM, and Jason-3, as well as by the LRO mission CryoSat-2 (both LRM and SAR data), and the NRO missions Envisat EM and SARAL DP.

With the UK approach, we interpolate water level time series for nine years at the locations of ten gauging stations along the Mekong River. In order to evaluate the ability to monitor extreme events in the annual flood, a flood index is defined, with which the flood extent can be compared inter-annually and between the different locations. The flood index indicates the difference between a flood for a specific year and the long term mean annual flood signal. Figure 2.14 visualizes the flood indices for all stations along the river for the UK time series, the in situ time series and the closest single-mission VS. The names of the stations are given together with the distances to the closest VS (negative values indicate that the VS is upstream from the gauge).

In the nine years considered here, the Mekong Basin was affected by two major flooding (above average flood) events in 2008 and 2011 and two below average floods in 2015 and 2016. The floodings are well seen in both the gauge data and the UK results, however, the extent of the flooding is overall underestimated by the UK time series. Only at the station Paksane the 2011 flooding is not seen at all in the UK time series. In comparison, only the Jason-2 VSs are able to observe the floodings as well, whereas many of the Envisat/SARAL VS time series cannot observe them. The anomalous low water levels in 2015 and 2016 are not seen by all UK time series but are overestimated by some VSs.

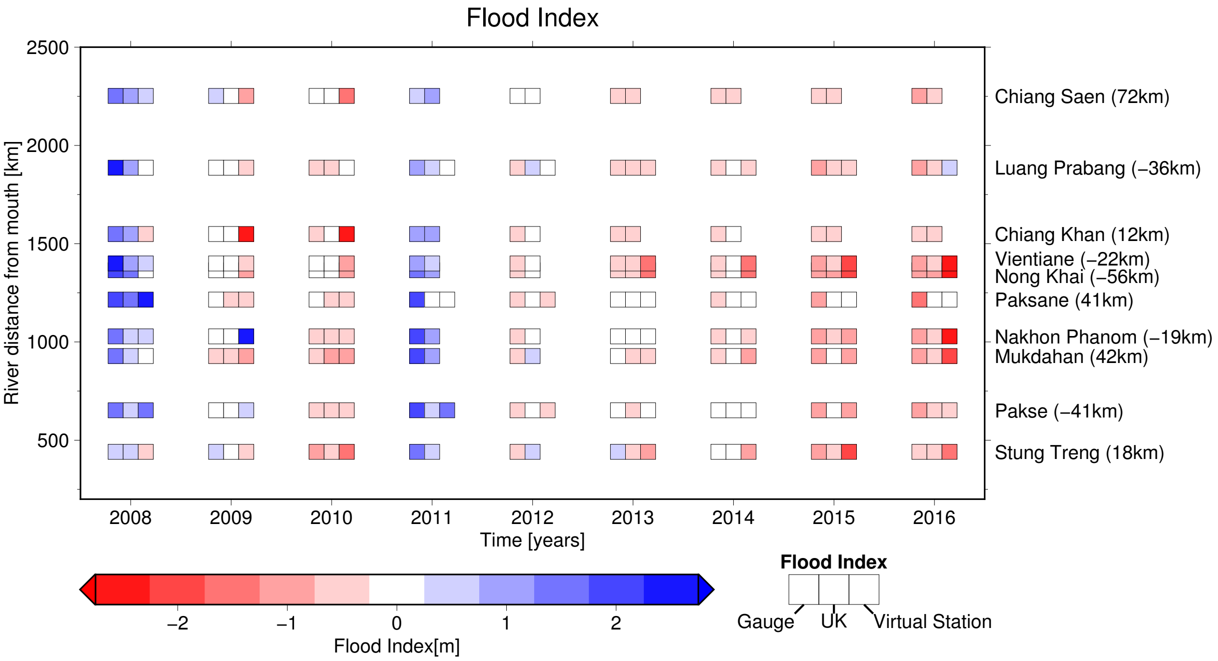

Fig. 2.14: *Flood index for all stations for the gauge data and the two UK results.*

The UK method also allows to forecast water levels at specific locations. This was tested for the two stations, Chiang Saen and Stung Treng, for a lead time of five days. Figure 2.15 shows the resulting time series between 2011 and 2016. Details of floods, in particular of flash floods, cannot be observed. Forecasting of water levels is more prone to outliers in the data which adds additional uncertainty to the results. At Chiang Saen the forecast overestimates the flood by several meters in 2011 and 2012. Excluding these years, the forecast reaches a MAE of 1.12 m compared to the official forecast of the Mekong River Commission between 0.75 and 1 m. At Stung Treng the forecast has an comparable quality with a MAE of 1.18 m.

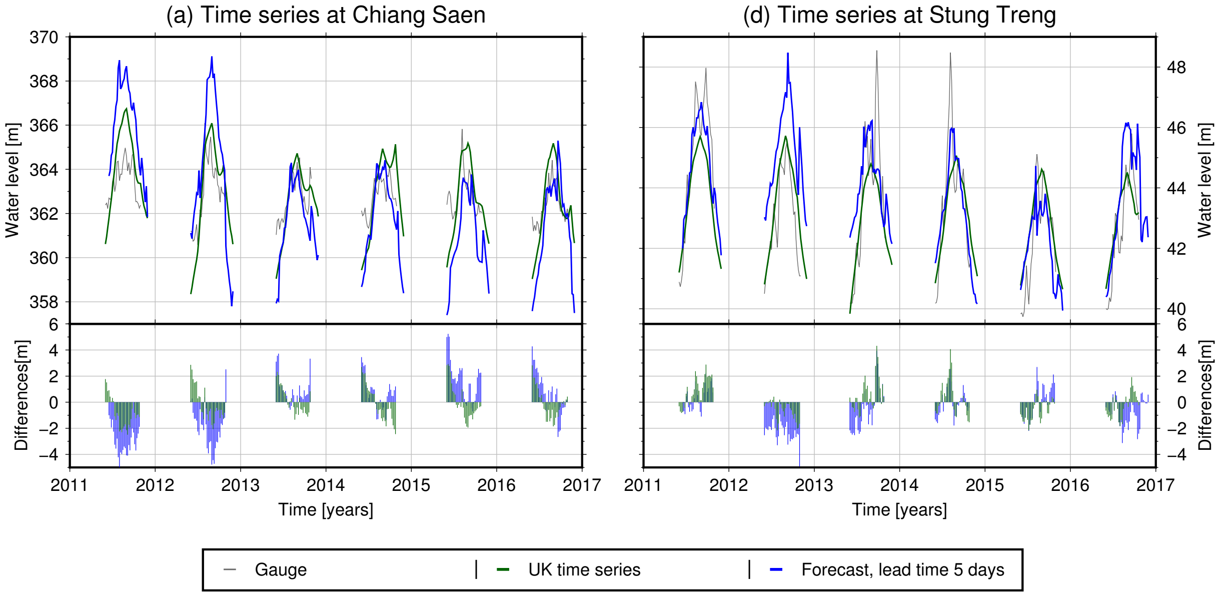

Fig. 2.15: *Interpolated time series at Chiang Saen and Stung Treng with a lead time of five days compared to the gauge and the UK time series. For each station the differences between gauge and the forecast time series are given as well.*

Horizontal water extent: a new supplement to the hydrological data base DAHITI

For many years, satellite altimetry has been proven to be a valuable tool for monitoring water levels of inland water bodies such as lakes, rivers and reservoirs. Besides the water stages, volume information of the water bodies is required for many hydrological applications. Time series of volume changes can be derived from a combination of water levels with information on the horizontal water extents. Since 2013, DGFI-TUM has been providing water levels derived from satellite altimetry via its Database for Hydrological Time Series of Inland Waters (DAHITI; http://dahiti.tum.de). In 2017, a new algorithm for the estimation of water surface extents of inland water bodies, called „Automated Water Area Extraction Tool“ (AWAX), has been developed. AWAX uses remote sensing data, in particular optical images of the Landsat missions, and automatically extracts water surfaces using the Google Earth Engine an a monthly basis. The Google Earth Engine brings new potential and applications for remote sensing data through its cloud-based data storage and geospatial data processing capabilities.

Time-consuming downloads of large satellite imagery data and raster files are largely reduced when using the Google Earth Engine. This allows to extend the data analysis to larger areas of interest. AWAX incorporated preprocessed Landsat images (1984-today) from which the best possible cloud-free monthly composites are used for the analysis.

The methodology of AWAX uses five different indices for the separation of land and water:

- Modified Normalized Difference Water Index (MNDWI)
- New Water Index (NWI)
- Automated Water Extraction Index for Non-Shadow Areas (AWEInsh)
- Automated Water Extraction Index for Shadow Areas (AWEIsh)
- Tasselled Cap for Wetness (TCw)

The indices are applied to the monthly composites, and adaptive thresholds are used to classify water areas. The combination of all resulting index masks leads to a final monthly mask that can still contain data gaps caused by clouds, snow or missing data. Remaining gaps are subsequently filled by a land-water probability mask based on more than 25 years of Landsat data.

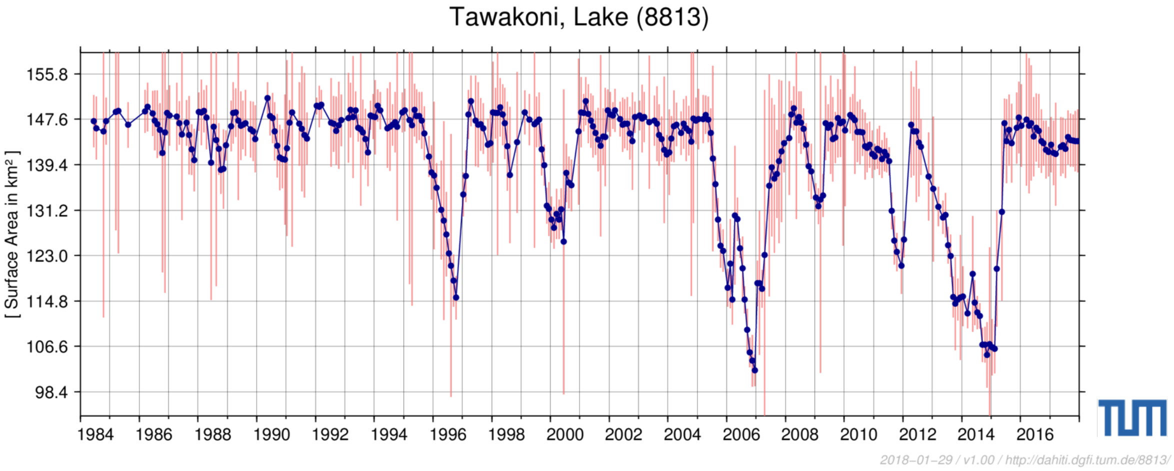

Fig. 2.16: *Time series of the water surface extent of Lake Tawakoni (with error bars).*

AWAX provides long-term inundation probability masks, monthly maps, and time series of water extent. Figure 2.16 shows as an example the time series of Lake Tawakoni. Variations of the surface area of this reservoir (dahiti.dgfi.tum.de/8813/) are clearly visible. Error bars are provided for each value of the time series, where the error is a sum of different contributions, such as data gaps, clouds or snow cover. The relation of water extent and water level (in-situ data of the gauge station Willis Point) for this particular lake is provided in Figure 2.17. The time series of water extent from AWAX will be made available in DAHITI soon where they will complement the DAHITI water level time series.

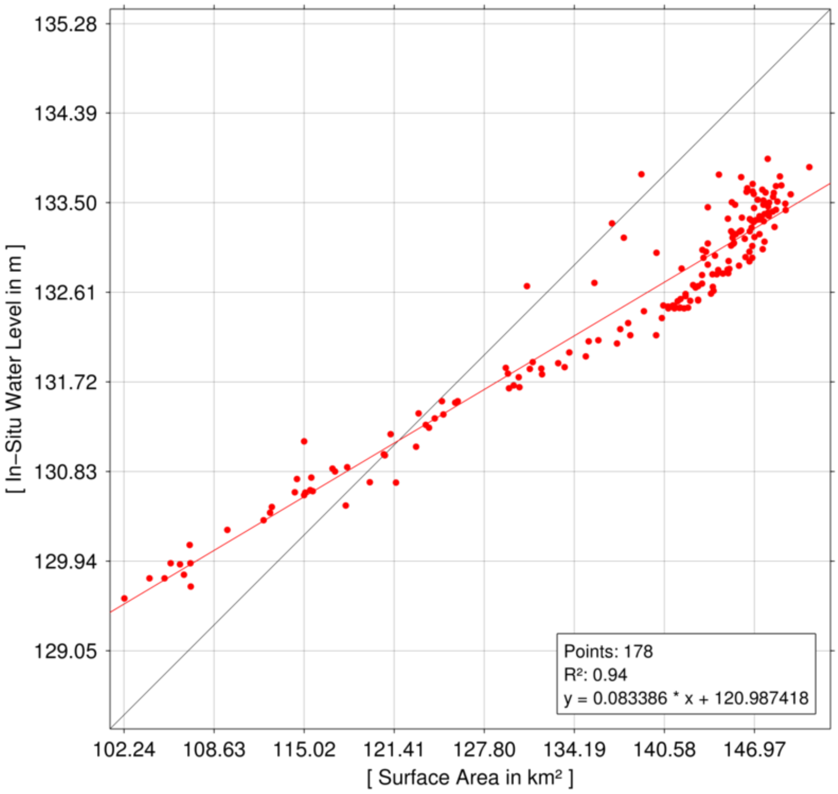

Fig. 2.17: *Relation between water extent and in-situ water level (gauge station Wills Point) for Lake Tawakoni.*

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M., Cazenave A., Benveniste J.: An improved and homogeneous altimeter sea level record from the ESA Climate Change Initiative. Earth System Science Data, 10, 281-301, doi: 10.5194/essd-2017-116, 2018

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3 Cross-Cutting Research Topics

The three overarching research topics Atmosphere, Regional Gravity Field, and Standards and Conventions are highly cross-related to the research areas Reference Systems and Satellite Altimetry for which they provide important contributions.

The atmosphere (Section 3.1) affects all space geodetic measurement techniques. On the one hand, atmospheric effects such as refraction or signal delay are major error sources which need to be considered. Thus, the optimisation of respective corrections and models means an important research challenge. On the other hand, the observation data of various geodetic measurement techniques that are influenced by the atmosphere in different ways provide valuable information on the state and the dynamics of the atmosphere. This information is of great interest for other disciplines such as meteorology or navigation. In particular, DGFI-TUM has built up strong experience in the modelling and prediction of global and regional physical structures of the Earth's ionosphere (4D electron content, space weather) from the joint analysis of space geodetic observations.

The precise knowledge of the Earth's gravity field (Section 3.2) is vital for various applications in geodesy, such as the realization and unification of height systems and the determination of high-precision satellite orbits. The latter are a prerequisite for the computation of accurate reference frames or for reliable estimates of water heights from satellite altimetry. Furthermore, the geoid provides the reference surface for the ocean circulation. Temporal changes of the gravity field contain information about mass transports in the Earth system and are of great interest, for example, for the investigation of dynamic processes in the Earth's interior or within the hydrosphere. DGFI-TUM primarily focuses on theoretical and practical aspects of regional gravity field determination. The goal is the creation of high-resolution and high-precision potential fields for delimited areas through a combination of various available data sets, e.g. satellite gravity field information, satellite altimetry, or terrestrial and airborne gravity data.

A fundamental prerequisite for any meaningful combination of different data sets is the definition and application of common standards and conventions (Section 3.3) in order to assure highest consistency of parameters and products. In the frame of the Global Geodetic Observing System (GGOS) DGFI-TUM manages the GGOS Bureau of Products and Standards (BPS) that is jointly operated with partners of the FGS. Furthermore DGFI-TUM leads two GGOS Focus Areas, namely the Focus Area on the Unified Height System and the Focus Area on Geodetic Space Weather Research.

3.1 Atmosphere

The Earth's atmosphere can be structured into various layers depending on different physical parameters such as temperature or charge state. In the latter case we distinguish mainly between the neutral atmosphere up to roughly 50 km altitude and the ionosphere approximately between 50 km and 1000 km altitude.

The Earth's ionosphere plays a key role in monitoring space weather, because it responses to solar storms with an increase of the electron density. Space-geodetic observation techniques, such as terrestrial GNSS, satellite altimetry, space-borne GPS (radio occultation) and DORIS provide valuable global information about the state of the ionosphere. In this context the project OPTIMAP (Operational Tool for Ionospheric Mapping and Prediction), already presented in

DGFI-TUM's annual reports of the last years, deals with the deployment of an operational service for the provision of ionosphere information including the effects of solar events in near real-time. The goal of the project EU Horizon 2020 project AUDITOR (Advanced Multi-Constellation EGNSS Augmentation and Monitoring Network and its Application in Precision Agriculture), as introduced in the Annual Report 2016, is the implementation of a novel precise positioning technique into a customized GNSS receiver by using sophisticated ionosphere models to increase the accuracy in real-time at the user side. Due to the coupling processes between the ionosphere and the thermosphere space weather is also affecting the thermospheric drag and, thus, it influences the movement, i.e. the orbit of a satellite. In this context the project INSIGHT (Interactions of Low-orbiting Satellites with the Surrounding Ionosphere and Thermosphere) aims on the improvement of thermosphere models by introducing SLR observations and ionosphere information.

Besides the three projects OPTIMAP, AUDITOR and INSIGHT, the project TIK (Development of an operational prototype for the determination of the thermospheric density on the basis of a coupled thermosphere-ionosphere model) is running at DGFI-TUM since March 2017. The main goal of TIK is the representation of the thermospheric density as a function of the ionospheric electron density by considering coupled thermosphere-ionosphere processes as realized within the physical model TIE-GCM (Thermosphere-Ionosphere-Electrodynamics General Circulation Model). Finally, a heuristic model of the thermospheric drag including a prediction part for operational use will be developed within TIK.

Since the research programme of DGFI-TUM's atmosphere group include (1) the computation of high-resolution global and regional models of the vertical total electron content (VTEC) within the ionosphere, (2) the application of Kalman filtering for near real-time and real-time modelling and (3) the development of forecast procedures, we present in the following the main results of DGFI-TUM's part of the AUDITOR project, since it comprises the three aforementioned items. Furthermore, we deal with the improvement of thermospheric density models by using SLR observations as studied within the INSIGHT project.

Real-time regional ionosphere maps: EU Horizon 2020 project AUDITOR

The International GNSS Service (IGS) delivers large volumes of GNSS data with different latencies, e.g., in real time (RT) or as hourly batches acquired from continuously operating terrestrial GNSS receivers distributed all over the globe. In addition to that, the IAAC's provide since nearly two decades VTEC maps denoted as final products with a latency of a few days. This effort has been extended to RT ionosphere products through the IGS RT ionosphere working group. Besides IGS various other groups are studying the exploitation of RT GNSS data to support RT applications. The AUDITOR project as mentioned before is aiming on the development of an improved GNSS ground-based augmentation system, e.g., for precision agriculture services to farmers. DGFI-TUM is contributing to this project by developing high precision RT ionosphere models using publicly available GNSS data.

Since the global data distribution and coverage of the IGS RT GNSS stations is still rather inhomogeneous and insufficient for global high precision RT ionosphere modelling, regional networks, such as EUREF, offer a much higher data distribution. Hence, within the AUDITOR project the Two-Level-Model (TLM), already presented in DGFI-TUM's Annual Report 2016, was extended for RT ionosphere modelling and applications. The different steps of this hybrid approach, formulated as

$$VTEC^{\mathrm{RT}}_{\mathrm{reg}}(\varphi,\lambda) = VTEC^{\mathrm{FC}}_{\mathrm{glob}}(\varphi,\lambda) + \Delta VTEC^{\mathrm{RT}}_{\mathrm{reg}}(\varphi,\lambda)\,, \tag{3.1}$$

are shown in Fig. 3.1 and discussed in detail in Schmidt et al. (2017). The procedure starts

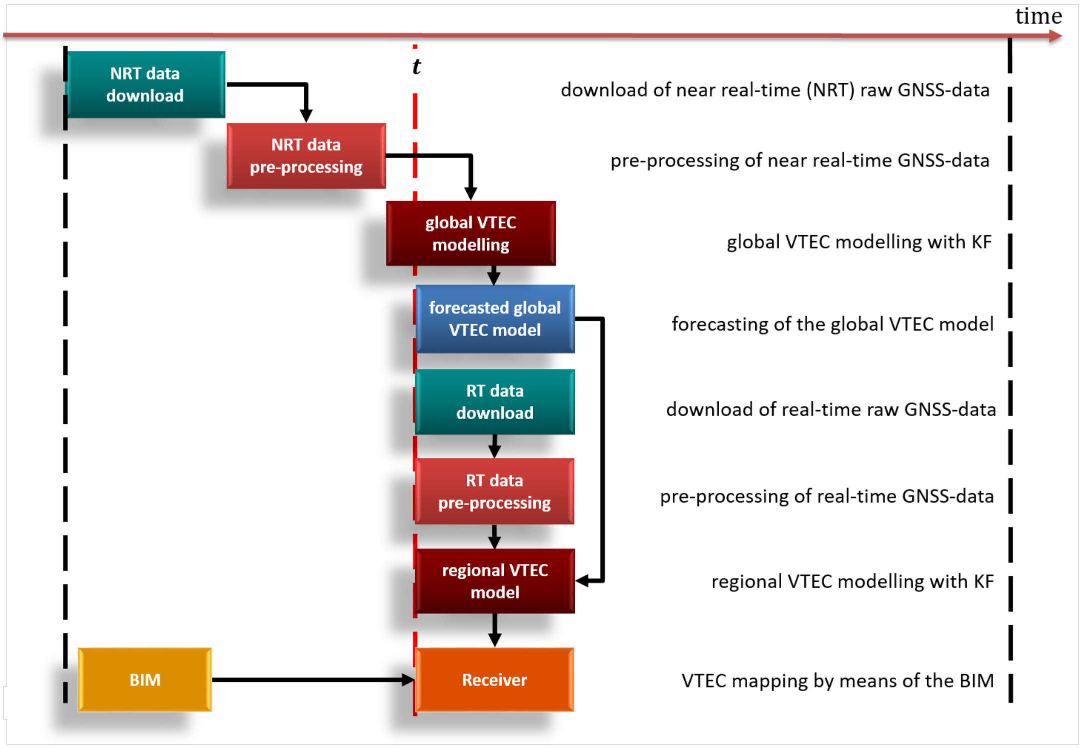


Fig. 3.1: *Hybrid procedure to compute global NRT maps, applying a forecast model and establishing regional RT VTEC maps; the forecast model part is shown in detail in Fig. 3.2; KF = Kalman filter, BIM = Barcelona Mapping Function.*

with the estimation of the global VTEC model $VTEC_{\text{glob}}^{\text{NRT}}$ in near-real time (NRT), see Erdogan et al. (2017). This result is then forecasted to present time to obtain the background information $VTEC_{\text{glob}}^{\text{FC}}$ for a chosen regional densification area. In parallel, RT GNSS data are downloaded and used to estimate the regional densification $\Delta VTEC_{\text{reg}}^{\text{RT}}$.

For the realization of the hybrid approach (3.1) hourly NRT observables $\widetilde{L}_{r,\text{NRT}}^{s}$ derived from GPS and GLONASS measurements between a satellite s and a terrestrial receiver station r are used. The observation equation reads

$$\widetilde{L}_{r,\text{NRT}}^{s} + e_r^s \;=\; \alpha \cdot M(z) \cdot VTEC_{\text{glob}}^{\text{NRT}} + b_r + b^s \,, \tag{3.2}$$

where e_r^s is the measurement error, α means a conversion factor and $M(z)$ refers to a mapping function depending on the zenith angle z. Furthermore, b_r and b^s stand for the receiver and satellite differential code biases (DCB), respectively. Within a Kalman filter (KF) procedure the unknown parameters including the coefficients $d_{k_1,k_2}^{J_1,J_2}(t)$ of the global VTEC representation defined as a series expansion in tensor products of polynomial B-splines $N_{J_1,k_1}^{2}(\varphi)$ depending on latitude φ and trigonometric B-splines $T_{J_2,k_2}^{2}(\lambda)$ depending on longitude λ are estimated; see the upper part of Fig. 3.2.

Within the forecast (FC) step the global VTEC maps are transferred to the present time moment t. As shown in Fig. 3.2 the FC model consists of a stochastic and a deterministic part. For the latter we chose a Fourier series with a basic period of $T_1 = 1$ day. The Fourier series coefficients $a_0, a_1, \ldots, a_n$ and $b_1, \ldots, b_n$ are independently estimated for each pair (k_1, k_2) by evaluating the time series of all B-spline coefficients $d_{k_1,k_2}^{J_1,J_2}(t)$ over a predefined time window, e.g., the 5 previous days. Once the Fourier series coefficients are estimated the remaining residual signal

$$X_{k_1,k_2}(t) \;=\; d_{k_1,k_2}^{J_1,J_2}(t) - \left\{ a_0 + \sum_{i=1}^{n} a_i \cos(\omega_i t) + b_i \sin(\omega_i t) \right\}_{k_1,k_2} \tag{3.3}$$

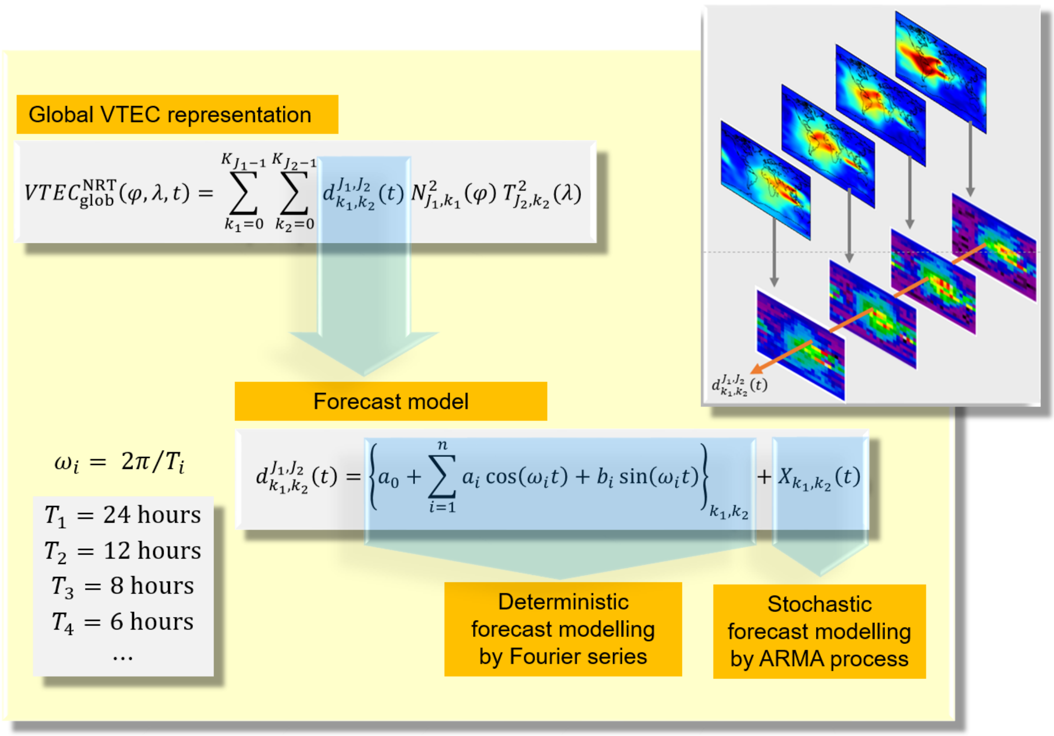


Fig. 3.2: *Forecast model consisting of a Fourier series as the deterministic part (periods are listed in the bottom left box) and an auto regressive moving average (ARMA) process as the stochastic model part; the panel top right shows both the time series of the B-spline coefficients* $d^{J_1,J_2}_{k_1,k_2}(t)$ *as well as the global VTEC maps* $VTEC^{\mathrm{NRT}}_{\mathrm{glob}}(\varphi,\lambda,t)$.

is modelled as an ARMA process which represents the stochastic part of the approach. Within the ARMA model as presented in Fig. 3.3, the coefficients $\Phi_1,..,\Phi_p$ and $\theta_1,...,\theta_q$ of the autoregressive part and the moving average part, respectively, are estimated using a Maximum-Likelihood estimator. The selection of the order values p and q of the ARMA(p,q) process model have been accomplished by manually conducting tests using autocorrelation and partial-

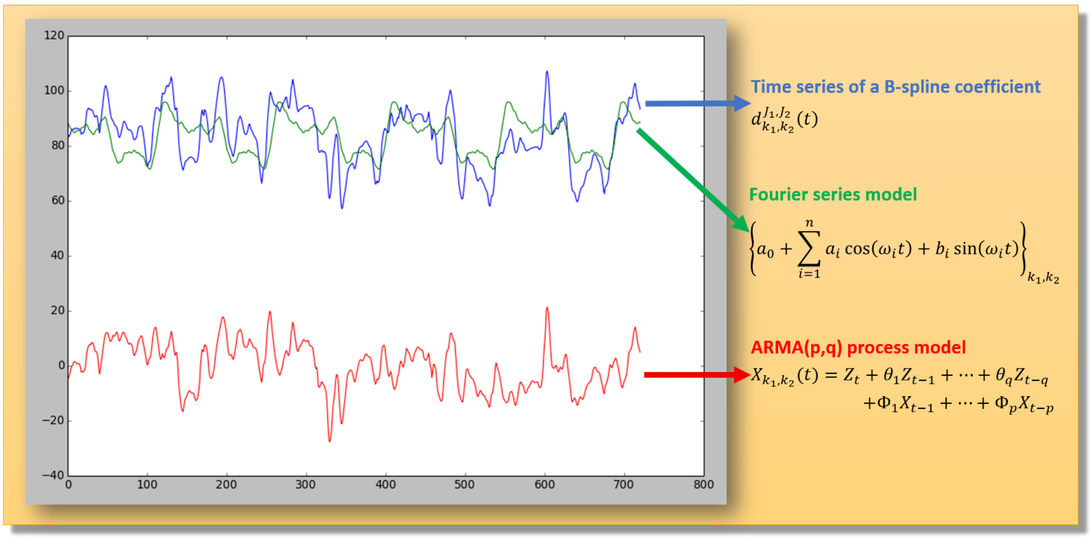


Fig. 3.3: *Application of the forecast model to the time series of an individual B-spline coefficient* $d^{J_1,J_2}_{k_1,k_2}(t)$ *given within a time interval of 5 days. The ARMA(p,q) process model consists of an autoregressive part represented by the noise values* $Z(t-j\cdot h) = Z_{t-j}$ *with* $j = 0,1,\ldots,q$ *and the moving average part including the residual signal values* $X_{k_1,k_2}(t-i\cdot h) = X_{t-i}$ *with* $i = 1,2,\ldots,p$; h *means the sampling interval of the VTEC maps.*

autocorrelations functions. Figure 3.3 shows an example for the overall estimation procedure applied to a given time series of an individual B-spline coefficient for a 5 days time interval. The performance of the FC model for 1 hour and 2 hours ahead is depicted in Fig. 3.4. It has to be stated that the contribution of the ARMA model is significantly considerable in short term forecasting. In the current implementation, its effect is vanishing within a few hours.

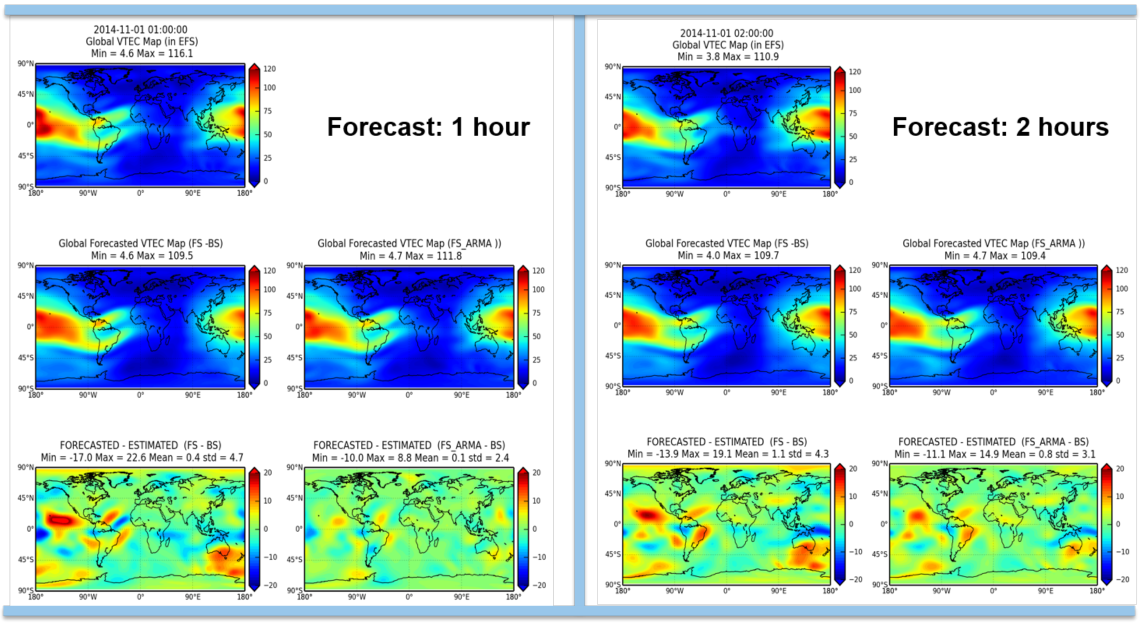


Fig. 3.4: *Two examples for the forecast model applied to the VTEC maps: on the left a 1 hour ahead forecast and on the right the 2 hours ahead forecast are presented. For both examples the panels from top to bottom, respectively, show the estimated VTEC product, the forecasted VTEC products using the Fourier series (FS) only on the left and the sum of the FS and the ARMA model on the right as well as the corresponding differences.*

In certain regions such as Europe, North America, Japan or parts of South America, RT GNSS data exist which could be used for a regional densification. To be more specific, we assume in our hybrid approach that within a rectangular area $\Delta\Omega$ of size $\Phi \times \Lambda$ high-resolution GNSS observations in RT are available. Herein, Φ means the extension of the area $\Delta\Omega$ with respect to the geographical latitude φ and Λ is the stretch of $\Delta\Omega$ with respect to the geographical longitude λ. Note, whereas the global model in our approach is defined within the Geocentric Solar Magnetic (GSM) coordinate system, the regional model is related to the geographical coordinate system.

The model for the high-resolution ionosphere variations within the densification area $\Delta\Omega$, i.e. $\Delta VTEC^{\mathrm{RT}}_{\mathrm{reg}}$ as introduced in Eq. (3.1), is set up as a 2-D series expansion in terms of tensor products of the normalized quadratic endpoint-interpolating B-spline functions $N^2_{J,k}$ with respect to latitude and longitude, i.e.

$$\Delta VTEC^{\mathrm{RT}}_{\mathrm{reg}}(\varphi,\lambda,t) = \sum_{k_3=0}^{K_{J_3}-1} \sum_{k_4=0}^{K_{J_4}-1} d^{J_3,J_4}_{k_3,k_4}(t)\, N^2_{J_3,k_3}(\varphi)\, N^2_{J_4,k_4}(\lambda)\,. \tag{3.4}$$

The most important point in the determination of the level values J_3 and J_4 is the spectral connection of the global and the regional model part. To be more specific, the smallest wavelength of the global model must be shorter or equal than the largest one of the regional model. Following this requirement the inequality relations $\Phi[\mathrm{km}] > \pi \cdot R/2^{J_1-1}$ and $\Lambda[\mathrm{km}] > R/2^{J_2-2}$ with respect to the global level values J_1 and J_2 can be set up, wherein R denotes the radius of the Earth in the unit 'kilometre'. With the given numerical values for the average sampling intervals $\Delta\varphi[\mathrm{km}]$ and $\Delta\lambda[\mathrm{km}]$ within the densification area we obtain for the level values J_3 and J_4 the inequality relations $J_3 < \log_2(\Phi/\Delta\varphi - 1)$ and $J_4 < \log_2(\Lambda/\Delta\lambda - 1)$.

In practice, the RT GNSS data given in RTCM (Radio Technical Commission for Maritime Services) format are downloaded using the BNC (BKG Ntrip Client) software of the Federal Agency for Cartography and Geodesy (BKG). The observation equation for the RT observables $\bar{\bar{L}}^s_{r,\mathrm{RT}}$ derived from GPS and GLONASS measurements reads

$$\bar{\bar{L}}^s_{r,\mathrm{RT}} + \bar{\bar{e}}^{\mathrm{s}}_r \;=\; \alpha \cdot M(z) \cdot \Delta VTEC^{\mathrm{RT}}_{\mathrm{reg}} + CPOB^s_r \,. \tag{3.5}$$

The reduced observations $\bar{\bar{L}}^s_{r,\mathrm{RT}}$ are obtained from the RT GNSS phase observation $\widetilde{L}^s_{r,\mathrm{RT}}$ according to

$$\bar{\bar{L}}^s_{r,\mathrm{RT}} \;=\; \widetilde{L}^s_{r,\mathrm{RT}} - \alpha \cdot M(z) \cdot VTEC^{\mathrm{FC}}_{\mathrm{glob}} \,. \tag{3.6}$$

In contrast to the levelled geometry-free NRT phase observations (3.2), where the relevant phase ambiguity biases are eliminated within the data pre-processing step, in the RT approach the phase related biases are directly estimated in the frame of Kalman filtering after comprising all biases to one parameter, namely the carrier phase observation bias $CPOB^s_r$. The reduced observations (3.6) are used to estimate the regional model part $\Delta VTEC^{\mathrm{RT}}_{\mathrm{reg}}(\varphi,\lambda)$. The corresponding series expansion (3.4) can be set up either in terms of uniform B-splines (UBS) or non-uniform B-splines (NABS); the NABS framework was introduced in DGFI-TUM's Annual Report 2015.

The hybrid densification approach (3.1) is performed continuously and recursively using the RT GNSS data and the forecasted background VTEC information. A Kalman filter is employed for sequential estimation of the regional target parameters including the regional B-spline model coefficients $d^{J_3,J_4}_{k_3,k_4}(t)$ from Eq. (3.4) as well as the biases defined in Eq. (3.5). The overall RT VTEC product generation according to Fig. 3.1 is generally accomplished in less than 30 seconds. The estimated VTEC information can be transferred to users, i.e. the receivers, either in form of the B-spline series coefficients or by VTEC grid values. We prefer the second option because in this case no encoding procedure are required for computing the regional VTEC values from B-spline series coefficients. Since VTEC information needs to be converted to STEC, a common way is to apply a standard isotropic mapping function $M(z)$ which neglects horizontal variations. Since, this way large mapping errors for GNSS measurements with low elevation angles may occur, a new and improved mapping function, named Barcelona Ionospheric Mapping (BIM) function, was developed by our project partners from the Universitat Politècnica de Catalunya for northern mid-latitudes; for more details on the whole procedure see Schmidt et al. (2017).

Figure 3.5 summarizes the overall procedure to establish regional VTEC maps in RT. The upper left panel represents the global ionospheric VTEC solution $VTEC^{\mathrm{NRT}}_{\mathrm{glob}}$ computed in NRT. Since we chose $J_1 = 4$ and $J_2 = 3$ the spatial resolution of these maps is comparable with the final maps provided by the IGS Ionosphere Associate Analysis Centers (IAAC), namely CODE in Berne, JPL in Pasadena, ESA in Darmstadt and UPC in Barcelona. In the next step the part of the map related to the area $\Delta\Omega = \Phi \times \Lambda$ of investigation (see the red-coloured box in the upper left panel in Fig. 3.5), i.e. the densification area, is forecasted to RT, i.e. to the present time moment t using the procedure visualized symbolically in Fig. 3.2. Following the inequality relations we presented before we obtained Φ[km] $>$ 2500 km as well as Λ[km] $>$ 3315 km and chose finally for the densification area $\Delta\Omega$ an extension of $\Phi[^\circ] = 30^\circ$ along the geographical meridian and $\Lambda[^\circ] = 40^\circ$ along the geographical equator and its parallels. The forecasted VTEC product $VTEC^{\mathrm{FC}}_{\mathrm{glob}}$ related to $\Delta\Omega$ is then used as the background model in the RT approach as shown in the right part of Fig. 3.5. As RT input we acquired data from the observation sites of the EUREF network. With the given numerical values $\Delta\varphi = 2.0^\circ$ and $\Delta\lambda = 4.0^\circ$ for the average sampling intervals with respect to latitude and longitude we obtained the level values $J_3 = 3$ and $J_4 = 3$. These values correspond to a spectral resolution of a global VTEC model in spherical harmonics up to degree $n = 30$. The final RT VTEC product is obtained by summing up the

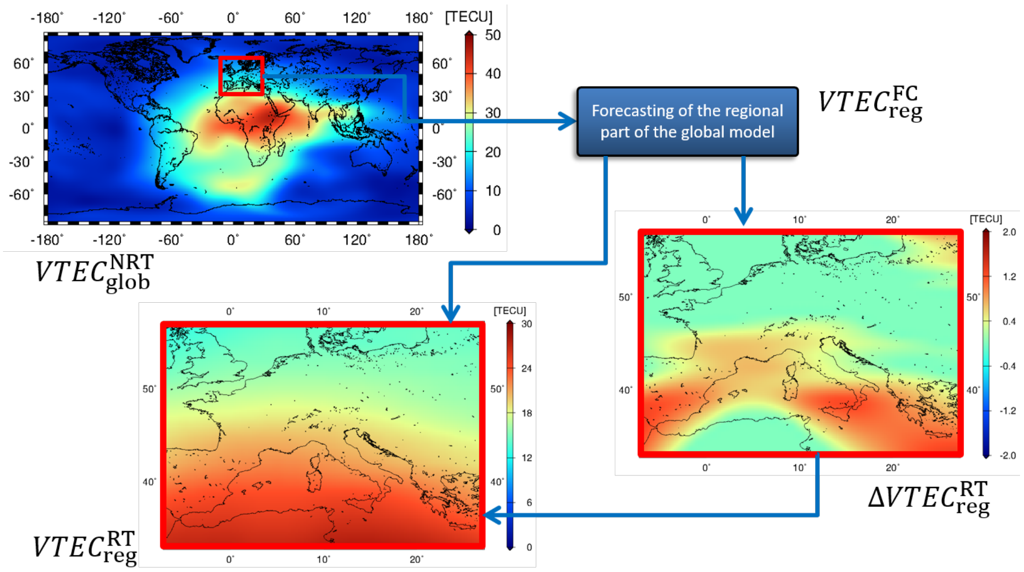


Fig. 3.5: *Regional RT high-resolution model* $VTEC_{\mathrm{reg}}^{\mathrm{RT}}(\varphi,\lambda,t)$ *(lower left panel) obtained from a combination of the forecasted global model* $VTEC_{\mathrm{glob}}^{\mathrm{FC}}$ *with the high-resolution regional model* $\Delta VTEC_{\mathrm{reg}}^{\mathrm{RT}}$ *(right panel).*

estimated regional $\Delta VTEC_{\mathrm{reg}}^{\mathrm{RT}}(\varphi,\lambda,t)$ map with the background VTEC map $VTEC_{\mathrm{glob}}^{\mathrm{FC}}(\varphi,\lambda,t)$ as illustrated in the bottom left panel of Fig. 3.5.

For the validation of the RT VTEC products the dSTEC analysis as introduced in DGFI-TUM's Annual Report 2016 is applied. In the given case, the products used for the validation are labelled as “codg”, “jplg”, “esag” and “upcg” provided by the four individual IAACs CODE, JPL, ESA and UPC. In this sense, the labels “regNABSrt” and “regUBSrt” refer to our estimated VTEC maps based on NABS and UBS, respectively. Furthermore, the solution just based on our forecast model is labelled as “fcUBS”. The geographical locations and the identifiers of the receiver stations selected for the evaluation are shown in Fig. 3.6. The receivers are chosen within Europe, i.e. the densification area $\Delta\Omega$.

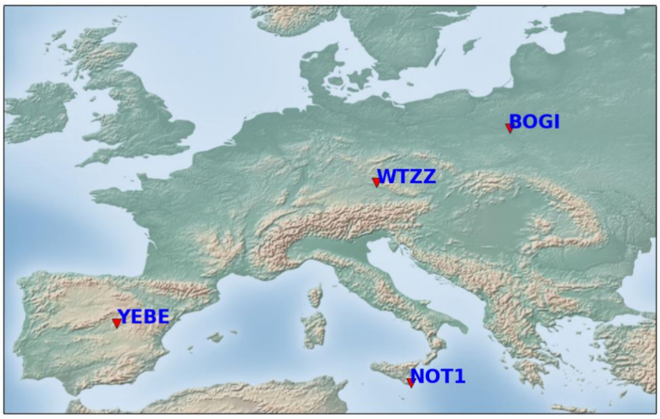


Fig. 3.6: *European receiver stations used for the dSTEC analysis of the regional RT VTEC products.*

In Fig. 3.7, as a summary of the statistical measures, the average mean values and the average standard deviations (STD) are presented for each of the four receiver stations shown in Fig. 3.6 for the entire test period. The larger dSTEC error for the observation site "NOT1" might be due to the limited number of receivers located in Southern Europe. In the figure, the values in parentheses in the legend show overall average values computed with respect to all four receivers. The validation analysis reveals that the presented approach is compatible with that of the final products of the analysis centers, however, we have to state that our model refers to a higher spectral content. A closer look to Fig. 3.7 reveals that the NABS solution shows smaller biases at the stations "NOT1" and "YEBE" compared to those of the UBS solution. The NABS approach also shows smaller standard deviations at the receiver stations "NOT1" and "BOGI". At the stations "WTZZ" and "BOGI" the standard deviations are almost identical for both the NABS and UBS solutions. As expected the solution “fcUBS” is the worst one, because it just comprises the forecast model values $VTEC_{\mathrm{reg}}^{\mathrm{FC}}$; cf. Fig. 3.5.

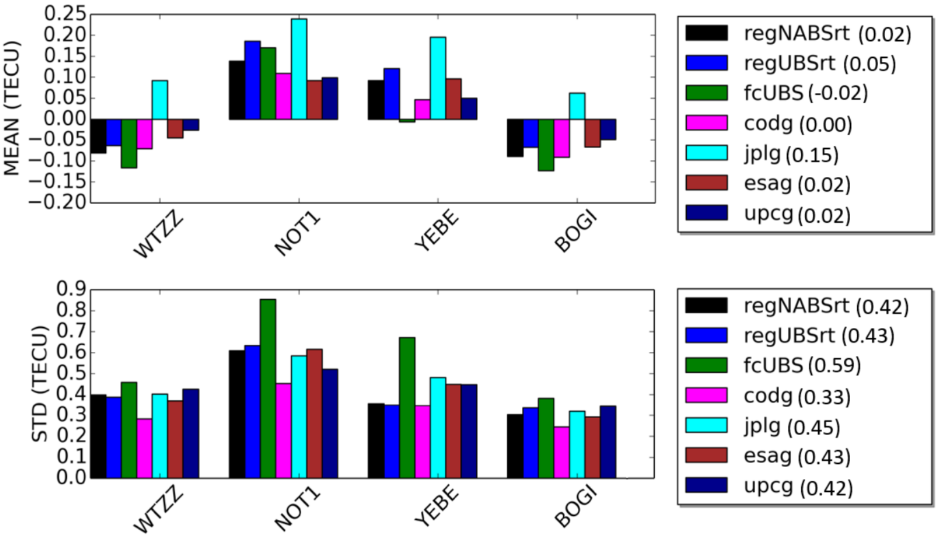


Fig. 3.7: *Results of the statistical evaluations presenting the differences between the observed and computed dSTEC values for the regional RT VTEC solution according to Fig. 3.5*

Thermospheric density estimation from Satellite Laser Ranging (SLR) observations to Low Earth Orbiting (LEO) satellites

The atmospheric drag is the major non-gravitational perturbation acting on LEO satellites up to around 1000 km causing an orbit decay. Since the atmospheric drag depends, among other parameters, on the thermospheric density, SLR measurements to spherical LEO satellites can be used to estimate scaling factors of the density given by various empirical thermospheric density models and, thus, provide corrections to these models and validate them (Panzetta et al. 2018; Rudenko et al., submitted). This procedure is not an easy task, since on the one hand, it requires a precise modelling of all other gravitational and non-gravitational perturbations acting on the satellites. On the other hand, the amount of SLR observations to LEO satellites is low as compared to that one of satellites at higher altitudes. These issues are conflictive with a precise orbit determination. However, within the project INSIGHT, we used SLR observations to the spherical satellites ANDE-P and ANDE-C launched in July 2009 as well as SpinSat launched in September 2014 to estimate scaling factors for the thermospheric density related to five empirical models, namely NRLMSISE-00, CIRA86, DTM2013, JB2008 and CH-Therm-2018; see Fig. 3.8. The latter was developed from our INSIGHT project partners at GFZ. This empirical model of the thermospheric mass density is derived from 9 years of CHAMP accelerometer measurements and can be used for altitudes between 330 km to 450 km; it describes the thermospheric mass density variations depending, e.g., on altitude, solar activity, season, local time, geographic latitude and longitude, and also to the geomagnetic activities; for more details see Chao et al., in revision.

The mean values of the scaling factors (see Table 3.1) show that all tested models, except CH-Therm-2018, overestimate the total thermospheric density (the values of the scaling factors are

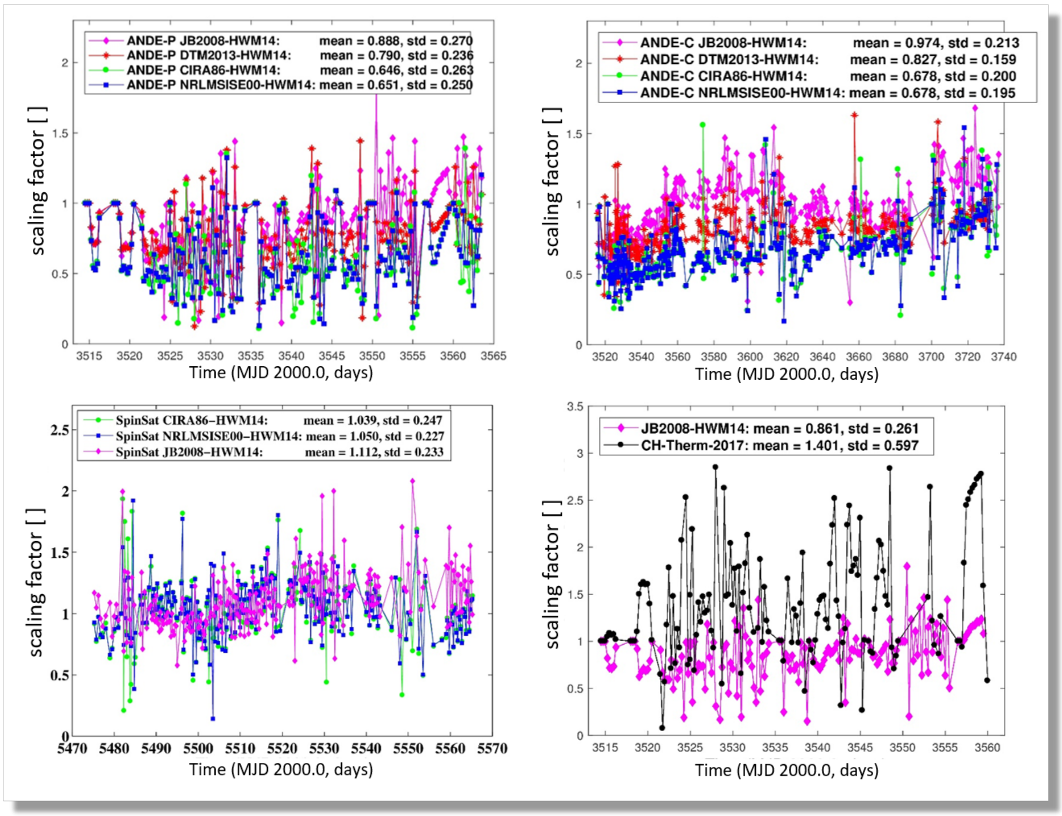


__Fig. 3.8:__ Estimated scaling factors for the thermospheric densities computed from NRLMSISE-00 (blue), CIRA86 (green), DTM2013 (red), JB2008 (magenta) and CH-Therm-2018 (black) by using SLR observations to ANDE-P from August 16, 2009 until October 3, 2009 (top left), ANDE-C from August 16, 2009 to March 26, 2010 (top right), SpinSat from December 29, 2014 to March 29, 2015 (bottom left) and ANDE-P from August 16, 2009 until September 30, 2009 (bottom right).

below 1.0) at the ANDE-C altitude of 297-350 km at the period of low solar activity from August 2009 until March 2010 and the ANDE-P altitude of 248 to 369 km in August and September 2009. The NRLMSISE-00, CIRA86 and JB2008 models, on the contrary, slightly underestimate the total thermospheric density (the values of the scaling factors are above 1.0) at the SpinSat altitude of 393 to 425 km at the period of high solar activity in January to March 2015. The DTM2013 model provides the smallest standard deviations of the estimated scaling factors, while the largest standard deviations are obtained for the CH-Therm-2018 model in case of ANDE-P.

__Table 3.1:__ Mean and standard deviations of the thermospheric density scaling factors for each thermosphere model (the wind model HWM14 is included) estimated from SLR measurements to each of the three satellites at the given time intervals.

Thermosphere model	ANDE-P 16.08.2009 – 03.10.2009	ANDE-C 16.08.2009 – 26.03.2010	SpinSat 29.12.2014 - 29.03.2015
CIRA86	0.646 ± 0.263	0.678 ± 0.200	1.039 ± 0.247
NRLMSISE00	0.651 ± 0.250	0.678 ± 0.195	1.050 ± 0.227
JB2008	0.888 ± 0.270	0.974 ± 0.213	1.112 ± 0.233
DTM2013	0.790 ± 0.236	0.827 ± 0.159	–
CH-Therm-2018	1.401 ± 0.597	–	–

An analysis of SLR observations to these and some other LEO satellites at longer time intervals should allow for a study on temporal variations of the scaling factors and a validation of the related thermosphere models at longer time intervals.

IAG GGOS Focus Area on Geodetic Space Weather Research

Space weather describes physical processes mainly caused by the Sun's radiation of energy. Manifestations of space weather are, e.g., the variations of the Earth's magnetic field or the changing state of the upper atmosphere, i.e. the ionosphere and the thermosphere. The most extreme known space weather event happened on September 1, 1859 – the so-called Carrington storm. Prominent recent, but weaker events are the Halloween storm on October 28 to 30, 2003, the Bastille Day Event on July 14, 2000 or the St. Patrick's storm on March 17, 2015. The potential strength of severe space weather events and their impact on modern society, e.g. the interruption of satellite services including GNSS and communication systems, have brought several countries such as the US and the UK to recognize the necessity, e.g., of studying these impacts scientifically. As a consequence of these activities the Focus Area on Geodetic Space Weather Research (FA-GSWR) was implemented under the umbrella of GGOS within the IAG. The main objectives of the FA-GSWR are

- the improvement in positioning and navigation by developing high-precision and high-resolution models of the electron density within the ionosphere,
- the improvement of precise orbit determination (POD) by developing high-precision and high-resolution thermospheric drag models, and
- the detailed study of the coupling processes between the thermosphere and the ionosphere.

The structure of the FA-GSWR can be visualized by a diamond as shown in Fig. 3.9. The different space-geodetic observation techniques provide valuable information about the state of the ionosphere and the thermosphere. Solar observations missions such as NASA's Advanced Composition Explorer (ACE) extend the observation plan, e.g. by including direct information on

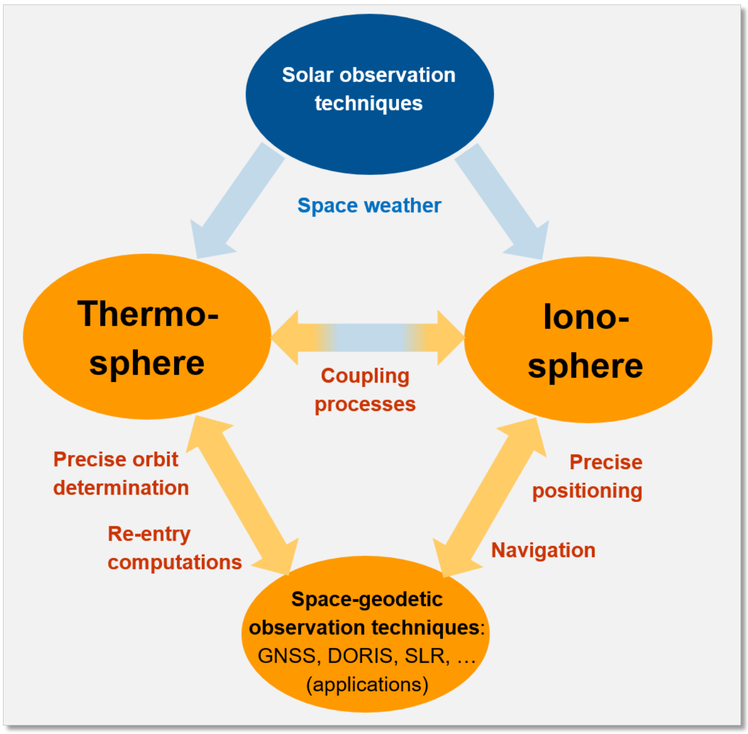


Fig. 3.9: Structure of the FA-GSWR: the orange-coloured parts are related to geodetic applications such as POD and precise point positioning and navigation; the blue-coloured parts are related to solar phenomena especially the space weather events.

space weather events. Consequently, geodetic space weather research has to be based on the use and combination of all space geodetic observation methods, the use of Sun observations from solar missions, data assimilation strategies, real-time modelling for prediction and the development of deterministic and stochastic forecast approaches. More details can be taken from the GGOS web site about the FA-GSWR (176.28.21.212/en/focus-areas/geodetic-space-weather-research/).

Related publications

Erdogan E., Schmidt M., Seitz F., Durmaz M.: Near real-time estimation of ionosphere vertical total electron content from GNSS satellites using B-splines in a Kalman filter. Annales Geophysicae 35(2), 263–277, doi:10.5194/angeo-35-263-2017, 2017

Liang W.: A regional physics-motivated electron density model of the ionosphere. PhD thesis, Technical University of Munich, 2017

Panzetta F., Bloßfeld M., Erdogan E., Rudenko S., Schmidt M., Müller H.: Absolute thermospheric density estimation from SLR observations of LEO satellites - A case study with ANDE-Pollux satellite. Journal of Geodesy, in press, 2018

Rudenko S., Schmidt M., Bloßfeld M., Xiong C., Lühr H.: Calibration of empirical models of thermospheric density using satellite laser ranging observations to near-Earth orbiting spherical satellites. IAG Symposia, submitted

Schmidt M., Erdogan E., Goss A., Hernández-Pajares M., García Rigo A., Lyu H.: Development and validation of sequential UBS and NABS models, http://auditor-project.eu/resources.html, 2017

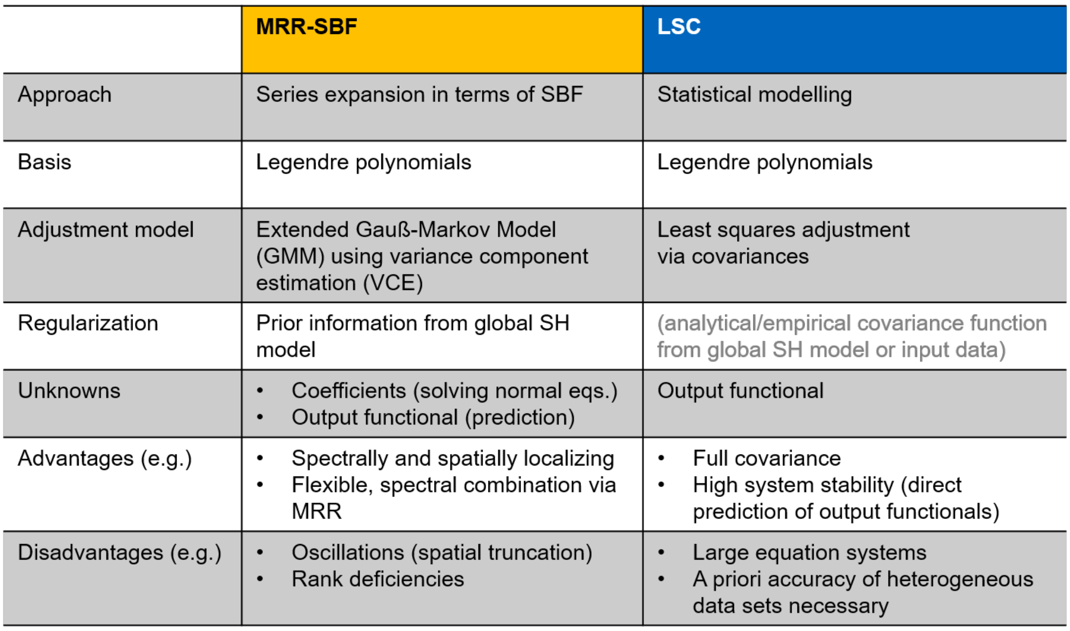
Xiong C., Lühr, Schmidt M., Bloßfeld M., Rudenko S.: An empirical model (CH-Therm-2018) of the thermospheric mass density derived from CHAMP. Annales Geophysicae, submitted

3.2 Regional Gravity Field

Since March 2016 the DFG funded project “Optimally combined regional geoid models for the realization of height systems in developing countries” with the acronym ORG4Heights runs jointly at the DGFI-TUM and the Chair of Astronomical and Physical Geodesy of the TUM. The main objective of ORG4Heights is the formulation of a general scientific concept for the realization and establishment of height systems in countries with a low-quality terrestrial data basis, such as developing or newly industrializing countries, by using regionally enhanced gravity field models. This goal involves and requires the optimal combination of heterogeneous gravity data sets and the derivation of realistic error estimates. In regions with terrestrial data we expect an accuracy of around a few decimeters, in regions with a sparse or low-quality terrestrial data base the expected accuracy might be improved to centimeters. An improvement might be achieved by considering data from topographic masses.

ORG4Heights comprises a number of innovative key aspects, namely (1) a scientific study on height system realization in developing countries, (2) a methodological development of a regional combined gravity field determination for data-critical regions including uncertainty quantification, (3) a systematic investigation of omission errors for height system realizations, (4) a quantification and treatment of systematic errors in a practical realization of height systems, (5) the further development and practical realization of the pyramidal algorithm in the frame of multi-resolution-representation (MRR) and spectral data combination as well as (6) the set-up of recommendations for a height system realization in developing and newly industrialized countries as guidelines for science and administration.

At DGFI-TUM the applied modelling approach is based on the MRR since it can be used for an optimal data combination based on the spectral content of the data from different observation techniques as was already discussed in the previous annual reports of DGFI-TUM. In ORG4Heights the obtained results shall be validated both internally as well as externally by making use of external data sources, e.g., stemming from satellite altimetry. For the internal validation a simulation was performed to study the spectral combination of heterogeneous gravity data within two different modelling approaches, namely the statistical approach of Least Squares Collocation (LSC) and the MRR based on radial spherical basis functions (SBF) denoted as MRR-SBF. In order to draw mutual benefit from both approaches the mathematical fundamentals have been studied in detail, closed-loop scenarios based on simulated data have been performed, analyzed, and an optimized regional modelling strategy has been set up. The following Fig. 3.10 compares the MRR-SBF with the LSC.



	MRR-SBF	**LSC**
Approach	Series expansion in terms of SBF	Statistical modelling
Basis	Legendre polynomials	Legendre polynomials
Adjustment model	Extended Gauß-Markov Model (GMM) using variance component estimation (VCE)	Least squares adjustment via covariances
Regularization	Prior information from global SH model	(analytical/empirical covariance function from global SH model or input data)
Unknowns	• Coefficients (solving normal eqs.) • Output functional (prediction)	Output functional
Advantages (e.g.)	• Spectrally and spatially localizing • Flexible, spectral combination via MRR	• Full covariance • High system stability (direct prediction of output functionals)
Disadvantages (e.g.)	• Oscillations (spatial truncation) • Rank deficiencies	• Large equation systems • A priori accuracy of heterogeneous data sets necessary

Fig. 3.10: *Comparison of the MRR-SBF and the LSC.*

An intensive study of the theoretical foundations of the two approaches demonstrated their close relationship, but also their differences. These theoretical investigations are still ongoing.

Related publication

Lieb V.: Enhanced regional gravity field modeling from the combination of real data via MRR. PhD thesis, German Geodetic Research Institute, Technical University of Munich, DGK Reihe C, 795, Verlag der Bayerischen Akademie der Wissenschaften, ISBN 978-3-7696-5207-9, 2017

3.3 Standards and Conventions

Geodesy provides measurements of the time varying gravity, rotation, and shape of the Earth using geometric and gravimetric instruments located on the ground and in space. These measurements need to be accurate to better than a part per billion in order to advance our understanding of the underlying processes that are causing changes of these Earth's parameters. A fundamental requirement towards this aim is the definition and application of common standards and conventions for the analysis of the individual geodetic observations.

IAG's Global Geodetic Observing System (GGOS) is designed to unite these observations into one consistent frame with the highest precision available, needed for a reliable monitoring and precisely quantifying global change phenomena, such as deformations and mass redistributions of the Earth system and global sea level rise. The present organizational structure of GGOS is shown in Fig. 3.11. The GGOS Bureau of Products and Standards has been established as a key component to keep track of the standards and conventions used within IAG and to support GGOS in its goal to obtain geodetic products of highest accuracy and consistency. It shall also be noted that a new GGOS Focus Area "Geodetic Space Weather Research" (Chair: Michael Schmidt, DGFI-TUM) has been established in 2017 (see Sect. 3.1 "Atmosphere").

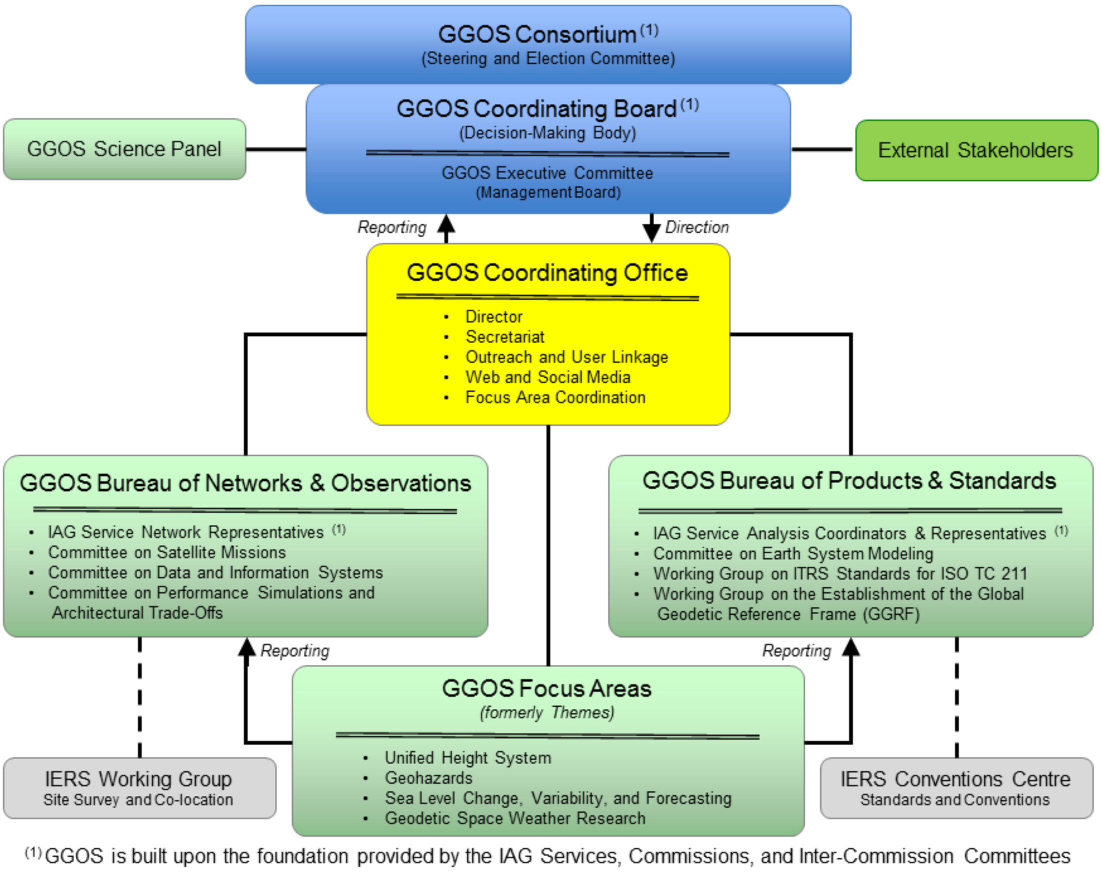


Fig. 3.11: Organizational structure of IAG's Global Geodetic Observing System (GGOS).

GGOS Bureau of Products and Standards

The BPS is chaired by the DGFI-TUM and operated jointly with the Chair of Astronomical and Physical Geodesy of the Technische Universität München within the Forschungsgruppe Satellitengeodäsie (FGS).

The main objectives of the BPS are:

- to serve as contact and coordinating point for the homogenization of IAG standards and products;
- to keep track of the adopted geodetic standards and conventions across all IAG components, and to initiate steps to close gaps and deficiencies;
- to focus on the integration of geometric and gravimetric parameters and to develop new geodetic products, needed for Earth sciences and society.

The present BPS staff members are D. Angermann (director), T. Gruber (deputy director), M. Gerstl, R. Heinkelmann (GFZ), U. Hugentobler, L. Sánchez and P. Steigenberger (DLR). In its current structure the following GGOS entities are associated with the BPS:

- Committee "Contributions to Earth System Modelling", Chair: M. Thomas (Germany),
- Joint Working Group "Establishment of the Global Geodetic Reference Frame (GGRF)", Chair: U. Marti (Switzerland),
- Working Group "ITRS Standards for ISO TC211", Chair: C. Boucher (France).

The Bureau comprises the staff members, the chairs of the associated GGOS components as well as representatives of the IAG Services and other entities. The present status of the associated members as BPS representatives is summarized in Table 3.2.

As regards the development of standards, there is a link with the IERS Conventions Center, the Commission A3 "*Fundamental Standards*" of the International Astronomical Union (IAU), the IAU Working Group "*Numerical Standards for Fundamental Astronomy*", the Bureau International de Poids et Mesures (BIPM), the Committee on Data for Science and Technology

Table 3.2: *Representatives of IAG Services and other entities (status: December 2017).*

IERS Conventions Center	G. Petit (until 2016) N. Stamatakos (since 2017)	BIPM (France) USNO (USA)
IERS Analysis Coordinator	T. Herring	MIT (USA)
IGS Representative	U. Hugentobler (BPS staff)	TUM (Germany)
ILRS Analysis Coordinator	E. Pavlis	UMBC/NASA (USA)
IVS Analysis Coordinator	J. Gipson	GSFC/NASA (USA)
IDS Analysis Coordinators	J.-M. Lemoine, H. Capdeville	CNES/GRGS (France)
IDS Representatives	F. Lemoine, J. Ries	GSFC, CSR (USA)
IGFS Chair	R. Barzaghi	Politecnico Milano (Italy)
BGI Chair	S. Bonvalot	IRD (France)
ISG President	M. Reguzzoni	Politecnico Milano (Italy)
ICGEM Chair	F. Barthelmes	GFZ (Germany)
IDEMS Director	K. Kelly	ESRI (USA)
IGETS Director	H. Wziontek	BKG (Germany)
Gravity Community (corresp. member)	J. Kusche	Univ. Bonn (Germany)
IAG Representative to ISO	J. Ihde (until 2016)	BKG, now GFZ (Germany)
IAG Communication and Outreach	J. Adam	Univ. Budapest (Hungary)
IAU Commission A3 Representative	C. Hohenkerk	HMNAO (United Kingdom)
IAU Representative	R. Heinkelmann (BPS staff)	GFZ (Germany)
Control Body for ISO Geodetic Registry	M. Craymer (Chair), L. Hothem (Vice Chair)	NRCan (Canada) USA

Table 3.3: *Comparison of numerical standards used within IAG.*

	semi-major axis a [m]	Geocentric gravitational constant GM [10^{12}m^{3}s^{-2}]	Dyn. form factor J_2 [10^{-6}]	Earth's rotation ω [rad s^{-1}]	Normal potential U_0 or W_0 [m^{2}s^{-2}]
GRS80 (1979)	6378137	398.6005	1082.63	7.292115	62636860.850
EGM2008	6378136.3	398.6004415(1)	1082.6359	7.292115	62636856.0 (1998)
IERS Conv. (2010)	6378136.6(2)	398.6004418(3)	1082.6359	7.292115	62636856.0 (1998)
IERS Conv. (2017)	6378136.6(2)	398.6004418(3)	1082.6359	7.292115	62636853.4 (2015)
IAG (2015)					62636853.4 (2015)

(1)TT-compatible value; (2)value given in zero-tide system; (3)TCG-compatible value

(CODATA), and the International Organization for Standardization (ISO) with its Technical Committee ISO/TC211.

According to its charter, a key activity of the BPS is to assess the standards and conventions currently adopted and used by the IAG and its components for the processing of geometric and gravimetric observations as a basis for the generation of IAG products. The document entitled "GGOS Bureau of Products and Standards: Inventory of standards and conventions used for the generation of IAG products" has been published in the IAG Geodesist's Handbook 2016 [1].

Status and recommendations on numerical standards

The BPS has performed an evaluation of the numerical standards that are presently in use within the geodetic community. This section summarizes the present status and recommendations on numerical standards. As shown in Table 3.3, different numerical standards are in use within the geodetic community. The values of the Geodetic Reference System 1980 (GRS80) are still used as official ellipsoid parameters, although it represents the scientific status of the 1970s. In the concept of GRS80, the tidal systems and relativistic theories are not considered (Ihde et al., 2017). The numerical standards of the IERS Conventions 2010 are commonly used for the processing of the geometric observations and for the generation of IERS products. The fact that the semi-major axis between GRS80 and IERS Conventions 2010 differs by 0.4 m is critical and has to be considered correctly for users of geodetic products. Table 3.3 also shows the numerical standards of the Earth Gravitational Model 2008 (EGM2008; Pavlis et al., 2012), which are partly different from the numerical standards given in the IERS Conventions. In cooperation between the IERS Conventions Center and the BPS, the conventional value W_0 = 62 636 853.4 m^{2}s^{-2} for the geopotential at mean sea level issued in the IAG (2015) Resolution No. 1 (Ihde et al., 2017; Sánchez and Sideris, 2017) has recently been updated in Chapter 1 of the IERS Conventions[2]. Thus, the former difference between the IERS Conventions 2010 value and the new IAG 2015 value of about -2.6 m^{2}s^{-2} (equivalent to a level difference of about 27 cm) has been resolved recently.

The current situation concerning numerical standards and the different use of time and tide systems is a potential source for inconsistencies and even errors of geodetic products. Thus, it is essential for a correct interpretation and application of geodetic results and products that the

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[1] Angermann D., Gruber T., Gerstl M., Heinkelmann R., Hugentobler U., Sánchez L., Steigenberger P.: GGOS Bureau of Products and Standards: Inventory of standards and conventions used for the generation of IAG products. In: Drewes H., Kuglitsch F., Adám J. (Eds.) The Geodesist's Handbook 2016. Journal of Geodesy 90(10), 1095–1156, 2016, doi:10.1007/s00190-016-0948-z, 2016

[2] Stamatakos N: Update IERS Conventions Chapter 1 (November 2017), `iers-conventions.obspm.fr/2010/2010_update/chapter1/icc1.pdf` and `maia.usno.navy.mil/conventions/2010/2010_update/chapter1/icc1.pdf`, 2017

underlying numerical standards are clearly documented. Moreover, the combination of geodetic results referring to different time or tide systems, transformations have to be performed to get consistent results.

The following recommendations on numerical standards have been specified in the BPS inventory, also endorsed as recommendations of the IAG/GGOS/IERS Unified Analysis Workshop 2017.

- **Recommendation 1** : The used numerical standards including time and tide systems must be clearly documented for all geodetic products.
- **Recommendation 2** : The geopotential value $W_0 = 62\,636\,853.4\,\mathrm{m}^2\mathrm{s}^{-2}$ issued by the IAG resolution No. 1 (2015) should be used as the conventional reference value for geodetic work.
- **Recommendation 3** : The development of a new Geodetic Reference System GRS20XX based on best estimates of the major parameters related to a geocentric level ellipsoid is desired.

Product-based review of standards and conventions

The following major topics were addressed in the product-based evaluation of standards and conventions (see chapter 4 in the BPS inventory, Angermann et al., 2016):

- Celestial reference systems and frames
- Terrestrial reference systems and frames
- Earth orientation parameters
- GNSS satellite orbits
- Gravity and geoid
- Height systems and their realizations.

IAG products exist for the celestial and terrestrial reference frames as well as for the EOP which are provided by the responsible Product Centers of the IERS (see www.iers.org). These products are derived from a combination of the contributing VLBI, SLR, GNSS and DORIS data. The IERS Conventions provide the basis for the work of the geometric IAG Services (IGS, ILRS, IVS and IDS), as well as for the definition and realization of geodetic reference systems and for the generation of IERS products. In addition to the IERS Conventions, several technique-specific standards are defined for the analysis of the individual geometric observations and technique-specific products (e.g., GNSS satellite orbits). The work of the BPS should be considered as a supplement to the extensive activities performed within the IAG Services and the IERS. The present issues concerning the analysis and combination of the geometric space-techniques were discussed during the IAG/GGOS/IERS Unified Analysis Workshop 2017. Detailed recommendations were provided in the report of the workshop[3].

Some general recommendations of the BPS inventory (Angermann et al., 2016) concerning the IERS products are provided below:

- At present, the celestial and the terrestrial reference frames and their integral EOP solutions are not fully consistent with each other as they are computed independently by separate IERS Product Centers. The Resolution No. 3 (2011) of the International Union of Geodesy and Geophysics (IUGG) recommends, that the highest consistency between the ICRF, the ITRF and the EOP as observed and realized by IAG and its components such as the IERS should be a primary goal in all future realizations of the ICRS.

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[3] Gross R, Herring T: Report of the GGOS/IERS Unified Analysis Workshop. Paris, France (2017/07/10-12), `176.28.21.212/media/filter_public/71/81/718149fd-b295-43dd-b82e-d01cacc8363e/uaw2017_report_v4.pdf`, 2017

- The processing standards and models should be consistently applied by all the analysis centers of the IAG Services providing data for the generation of the IERS products.
- The station networks and the spatial distribution of high quality co-location sites should be improved as a fundamental requirement to achieve the GGOS accuracy requirements as specified in the GGOS 2020 book.

The International Gravity Field Service (IGFS) is responsible to coordinate the gravity-related IAG Services (BGI, ISG, IGETS, ICGEM, IDEMS) and its overall goal is to provide gravity field related data, software and information for the scientific community. The IGFS Central Bureau has recently been established at the Aristotle University of Thessaloniki providing an updated IGFS website (www.igfs.topo.auth.gr), including a dedicated product portal for the download of data and results generated by the IGFS Services. As an example, about 170 models of the global gravity field of the Earth are made available to the public via the ICGEM website (icgem.gfz-potsdam.de). A recommendation is that a conventional global gravity field model might be useful as a reference model to be used for the generation of official IAG products, whereas scientific users should be free to use any preferred model for their particular purposes.

The last topic of the product-based inventory focuses on height systems and their realizations. In this field significant progress has been achieved in 2017 (see topic "Vertical reference systems" in Sect. 1.4).

Ongoing and planned activities

According to its Implementation Plan 2017-2018, the BPS focuses on the following activities:

- An ongoing activity of the BPS is to keep track of the geodetic standards and conventions adopted by IAG and its components for the generation of IAG products. The contents of the BPS inventory (Angermann et al., 2016) presents the status of January 15, 2016, and will be regularly updated as a "living document".
- Concerning the recommendations given in the BPS inventory a lot of progress has already been achieved and several activities have been initiated by the responsible IAG components. The BPS has taken over a coordinating role to initiate steps how to proceed with the recommendations that require further activities. Together with the representatives of the IAG Services and other involved entities (see Table 3.2) an action plan should be compiled, including a task description, specification of responsibilities and a time schedule.
- The BPS also supports the development of new products derived from a combination of geometric and gravimetric observations. Towards this aim various activities have been initiated and dedicated GGOS entities have been established to focus on the development of integrated products, such as the Focus Area “Unified Height System”, the newly established Focus Area “Geodetic Space Weather Research” and the Joint IAG Working Group “Establishment of the Global Geodetic Reference Frame (GGRF)” to support the activities of the United Nations (UN) in context with the UN resolution on a Global Geodetic Reference Frame for Sustainable Development (A/RES/69/266) adopted on February 26, 2015.
- The director of the BPS has been nominated by the IAG Executive Committee as the IAG Representative to the UN Global Geospatial Information Management (UN-GGIM) Subcommittee “Geodesy” (the former GGRF Working Group) for the Focus Group “Data Sharing and Development of Geodetic Standards”.

- Within IAU, the Division A Commission A3 “Fundamental Standards”, the Division Working Group “Numerical Standards in Fundamental Astronomy (NSFA)”, and the IAU’s Standards of Fundamental Astronomy (SOFA) service are directly involved in standards. A close link between these IAU components and the BPS ensures the interaction between the different components and enables regular exchange of information.
- Finally, the BPS also contributes to a gap analysis concerning IAG products. Towards this aim, it was agreed during the GGOS Days 2017 in Vienna that a Panel should be established to define a list of Essential Geodetic Variables (EGCs) and to assign requirements to them. It was proposed that the Panel should consist of representatives of the IAG Services and the members of the GGOS Science Panel representing the IAG Commissions, the Inter-Commission Committee on Theory, and the four GGOS Focus Areas. First steps towards the establishment of such a Panel on EGVs have been initiated by the BPS at the end of 2017.

Related publications

Ihde J, Sánchez L, Barzaghi R, Drewes H, Foerste Ch, Gruber T, Liebsch G, Marti U, Pail R, Sideris M: Definition and proposed realization of the International Height Reference System (IHRS). Surveys in Geophysics 38(3), 549–570, doi:10.1007/s10712-017-9409-3, 2017

Sánchez L, Sideris M: Vertical datum unification for the International Height Reference System (IHRS). Geophysical Journal International 209(2), 570–586, doi:10.1093/gji/ggx025, 2017

4 Information Services and Scientific Transfer

The DGFI-TUM is strongly cross-linked with other institutions worldwide. Intensive collaborations exist in particular in the frame of the international scientific organizations IUGG, IAU and IAG. The DGFI-TUM recognizes the outstanding role of the IAG Services that form the backbone for the national and international spatial data infrastructure by coordinating and supporting geodetic research on the international level. Within this framework, the institute operates - mostly by long-term commitments - data centers, analysis centers, and research centers (cf. Section 1) as well as various internet portals (Section 4.1). Scientists of DGFI-TUM have taken leading positions and supporting functions in IAG's Commissions, Services, Projects, Working and Study Groups, and in the Global Geodetic Observing System (GGOS). A complete list of memberships and functions of DGFI-TUM staff is given in Section 4.2. Publications in peer-reviewed scientific journals are still the most acknowledged way of scientific transfer. Section 4.3 provides a list of articles printed or published online in 2017. It is followed by a list of posters and oral presentations (Section 4.4) that were presented by DGFI-TUM staff at numerous national and international conferences, symposia and workshops (Section 4.5).

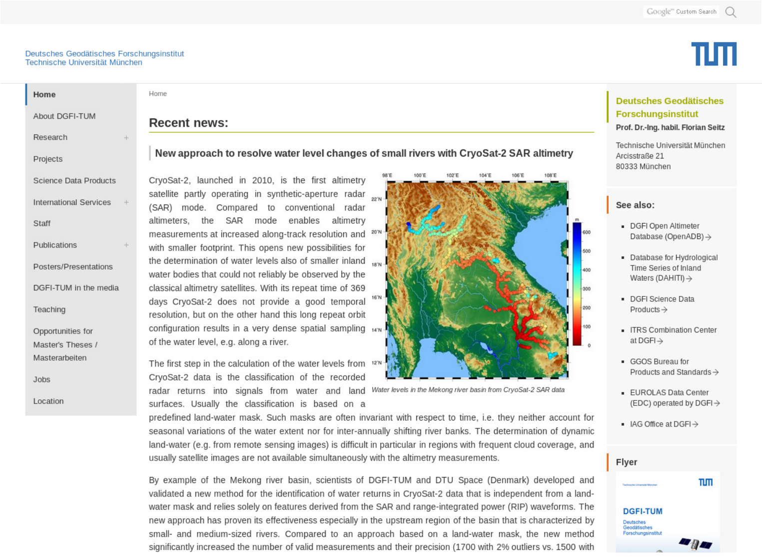
4.1 Internet representation

In order to meet the growing demand for scientific information and to exchange scientific results and data, DGFI-TUM operates several independent internet sites and mailing lists.

In 2017, DGFI-TUM maintained the following web sites:

Deutsches Geodätisches Forschungsinstitut der Technischen Universität München (DGFI-TUM)

The web site of DGFI-TUM at www.dgfi.tum.de highlights current research results and informs about the institute's structure and current research programme. It presents the national and international projects of DGFI-TUM as well as its contributions to various international scientific organizations. The web site (see Fig. 4.1) also provides a complete list of publications, reports and presentations since 1994. Annual Reports and DGFI Reports are available in electronic form.



Deutsches Geodätisches Forschungsinstitut
Technische Universität München

Recent news:

New approach to resolve water level changes of small rivers with CryoSat-2 SAR altimetry

CryoSat-2, launched in 2010, is the first altimetry satellite partly operating in synthetic-aperture radar (SAR) mode. Compared to conventional radar altimeters, the SAR mode enables altimetry measurements at increased along-track resolution and with smaller footprint. This opens new possibilities for the determination of water levels also of smaller inland water bodies that could not reliably be observed by the classical altimetry satellites. With its repeat time of 369 days CryoSat-2 does not provide a good temporal resolution, but on the other hand this long repeat orbit configuration results in a very dense spatial sampling of the water level, e.g. along a river.

Water levels in the Mekong river basin from CryoSat-2 SAR data

The first step in the calculation of the water levels from CryoSat-2 data is the classification of the recorded radar returns into signals from water and land surfaces. Usually the classification is based on a predefined land-water mask. Such masks are often invariant with respect to time, i.e. they neither account for seasonal variations of the water extent nor for inter-annually shifting river banks. The determination of dynamic land-water (e.g. from remote sensing images) is difficult in particular in regions with frequent cloud coverage, and usually satellite images are not available simultaneously with the altimetry measurements.

By example of the Mekong river basin, scientists of DGFI-TUM and DTU Space (Denmark) developed and validated a new method for the identification of water returns in CryoSat-2 data that is independent from a land-water mask and relies solely on features derived from the SAR and range-integrated power (RIP) waveforms. The new approach has proven its effectiveness especially in the upstream region of the basin that is characterized by small- and medium-sized rivers. Compared to an approach based on a land-water mask, the new method significantly increased the number of valid measurements and their precision (1700 with 2% outliers vs. 1500 with

Deutsches Geodätisches Forschungsinstitut
Prof. Dr.-Ing. habil. Florian Seitz

Technische Universität München
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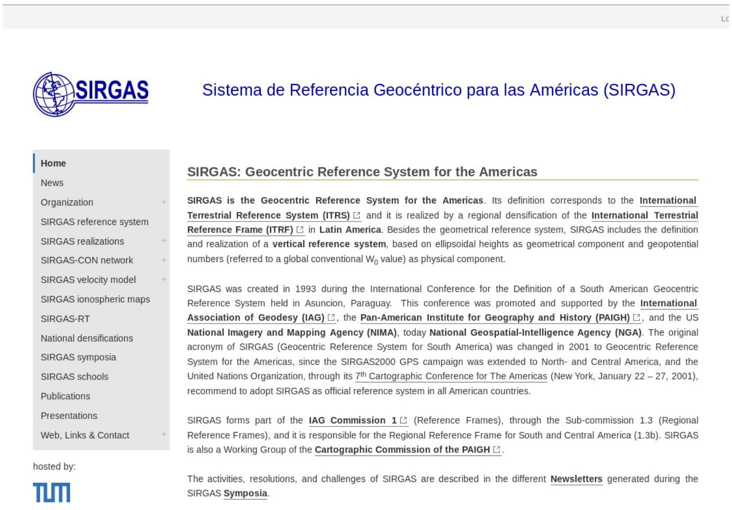
80333 München

See also:

- DGFI Open Altimeter Database (OpenADB) →
- Database for Hydrological Time Series of Inland Waters (DAHITI) →
- DGFI Science Data Products →
- ITRS Combination Center at DGFI →
- GGOS Bureau for Products and Standards →
- EUROLAS Data Center (EDC) operated by DGFI →
- IAG Office at DGFI →

Fig. 4.1: *Web site of DGFI-TUM at www.dgfi.tum.de*

Geocentric Reference System for the Americas (SIRGAS)



SIRGAS: Geocentric Reference System for the Americas

SIRGAS is the Geocentric Reference System for the Americas. Its definition corresponds to the **International Terrestrial Reference System (ITRS)** and it is realized by a regional densification of the **International Terrestrial Reference Frame (ITRF)** in **Latin America**. Besides the geometrical reference system, SIRGAS includes the definition and realization of a **vertical reference system**, based on ellipsoidal heights as geometrical component and geopotential numbers (referred to a global conventional W_0 value) as physical component.

SIRGAS was created in 1993 during the International Conference for the Definition of a South American Geocentric Reference System held in Asuncion, Paraguay. This conference was promoted and supported by the **International Association of Geodesy (IAG)**, the **Pan-American Institute for Geography and History (PAIGH)**, and the US **National Imagery and Mapping Agency (NIMA)**, today **National Geospatial-Intelligence Agency (NGA)**. The original acronym of SIRGAS (Geocentric Reference System for South America) was changed in 2001 to Geocentric Reference System for the Americas, since the SIRGAS2000 GPS campaign was extended to North- and Central America, and the United Nations Organization, through its 7th Cartographic Conference for The Americas (New York, January 22 – 27, 2001), recommend to adopt SIRGAS as official reference system in all American countries.

SIRGAS forms part of the **IAG Commission 1** (Reference Frames), through the Sub-commission 1.3 (Regional Reference Frames), and it is responsible for the Regional Reference Frame for South and Central America (1.3b). SIRGAS is also a Working Group of the **Cartographic Commission of the PAIGH**.

The activities, resolutions, and challenges of SIRGAS are described in the different **Newsletters** generated during the SIRGAS **Symposia**.

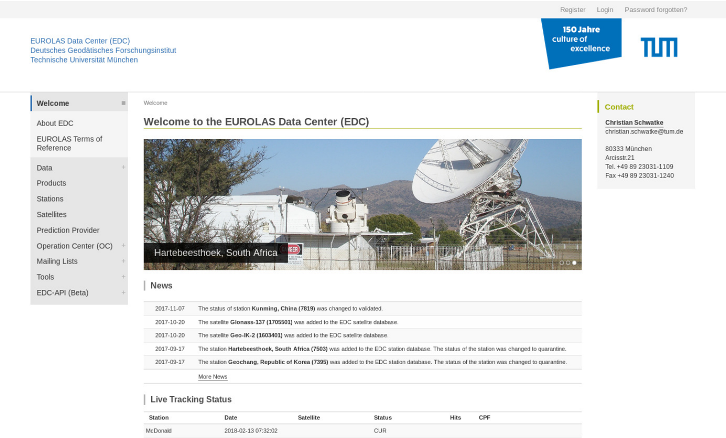
Fig. 4.2: *Web site of SIRGAS at www.sirgas.org*

SIRGAS is the Geocentric Reference System for the Americas. The web site (www.sirgas.org) is operated by the IGS Regional Network Associate Analysis Centre for SIRGAS (IGS RNAAC SIRGAS), which is under the responsibility of DGFI-TUM since 1996.

The SIRGAS web site provides (see Fig. 4.2)

- a scientific description of definition, realization, and kinematics of the SIRGAS reference frame,
- an organizational overview (operational structure and functions of the different components of SIRGAS),
- a bibliographic compilation related to SIRGAS activities (articles, reports, presentations).

EUROLAS Data Centre (EDC)



Welcome to the EUROLAS Data Center (EDC)

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Tel. +49 89 23031-1109
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News

2017-11-07	The status of station **Kunming, China (7819)** was changed to validated.
2017-10-20	The satellite **Glonass-137 (1705501)** was added to the EDC satellite database.
2017-10-20	The satellite **Geo-IK-2 (1603401)** was added to the EDC satellite database.
2017-09-17	The station **Hartebeesthoek, South Africa (7503)** was added to the EDC station database. The status of the station was changed to quarantine.
2017-09-17	The station **Geochang, Republic of Korea (7395)** was added to the EDC station database. The status of the station was changed to quarantine.

More News

Live Tracking Status

Station	Date	Satellite	Status	Hits	CPF
McDonald	2018-02-13 07:32:02		CUR		

Fig. 4.3: *Web site of EDC at edc.dgfi.tum.de*

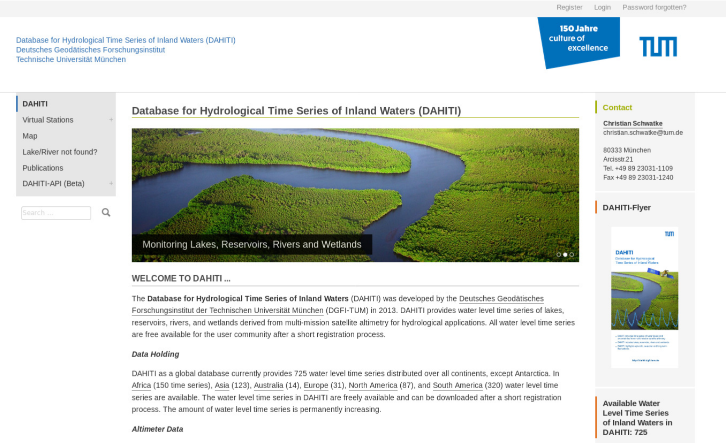
The EUROLAS Data Center (EDC) provides access to the database of SLR observations and derived products (see Fig. 4.3).
The web site at edc.dgfi.tum.de informs about the data flow within the Operation Centre (OC) and the data holding of the Data Centre (DC).

Open Altimeter Database (OpenADB)

OpenADB is a database for multi-mission altimeter data and derived high-level products. It is designed for both non-expert users and scientific users who are interested in the analysis and application of altimetry data in order to determine new products, models and algorithms. OpenADB allows for fast parameter updates and for extracting data and parameters in user-defined formats. OpenADB is open to the public at no charge after registration. The web site is available at openadb.dgfi.tum.de.

Database for Hydrological Time Series of Inland Waters (DAHITI)

The Database for Hydrological Time Series of Inland Waters (DAHITI) is a public repository of more than 700 water level time series of globally distributed lakes, rivers, reservoirs, and wetlands derived at DGFI-TUM from multi-mission satellite altimetry. The web site of DAHITI is available at dahiti.dgfi.tum.de (see Fig. 4.4).



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WELCOME TO DAHITI ...

The **Database for Hydrological Time Series of Inland Waters** (DAHITI) was developed by the Deutsches Geodätisches Forschungsinstitut der Technischen Universität München (DGFI-TUM) in 2013. DAHITI provides water level time series of lakes, reservoirs, rivers, and wetlands derived from multi-mission satellite altimetry for hydrological applications. All water level time series are free available for the user community after a short registration process.

Data Holding

DAHITI as a global database currently provides 725 water level time series distributed over all continents, except Antarctica. In Africa (150 time series), Asia (123), Australia (14), Europe (31), North America (87), and South America (320) water level time series are available. The water level time series in DAHITI are freely available and can be downloaded after a short registration process. The amount of water level time series is permanently increasing.

Altimeter Data

Available Water Level Time Series of Inland Waters in DAHITI: 725

Fig. 4.4: *Web site of DAHITI at dahiti.dgfi.tum.de*

GGOS Bureau of Products and Standards (BPS)

The GGOS Bureau of Products and Standards (BPS) was established as a component of IAG's Global Geodetic Observing System (GGOS) in 2009. The BPS is chaired by DGFI-TUM and operated jointly with partners from the Forschungsgruppe Satellitengeodäsie (FGS). The GGOS BPS web site is located at ggos-bps.dgfi.tum.de

GGOS Focus Area Unified Height System

DGFI-TUM chairs the GGOS Focus Area *Unified Height System* for the term 2015-2019. Its website is available at ihrs.dgfi.tum.de. The immediate objectives of this GGOS component are (1) the outlining of detailed standards, conventions, and guidelines to make the IAG Resolution on the International Height Reference System (IHRS) applicable, and (2) to establish the realization of the IHRS, i.e. the International Height Reference Frame (IHRF). The web page informs about current activities and achievements.

Office of the International Association of Geodesy (IAG)

Since the 24th General Assembly of the IUGG (2007) in Perugia, Italy, the DGFI has been hosting the Office of the International Association of Geodesy (IAG Office). For the same period, the former director of the DGFI has been holding the position of the IAG Secretary General. In this context, DGFI-TUM has taken the responsibility for the administration of the IAG budget. The web site of the IAG Office is available at iag.dgfi.tum.de

4.2 Membership in scientific bodies

Ausschuss Geodäsie der Bayerischen Akademie der Wissenschaften – Deutsche Geodätische Kommission (DGK)

- *Member: Seitz F.*

Centre National d'Etudes Spatiales (CNES) / National Aeronautics and Space Administration (NASA)

- Ocean Surface Topography Science Team,
  Member: Dettmering D., Passaro M., Schwatke C.

Deutsche Gesellschaft für Geodäsie, Geoinformation und Landmanagement (DVW)

- Working Group 7: Experimentelle, Angewandte und Theoretische Geodäsie,
  Member: Schmidt M., Seitz F.

European Commission (EC) / European Space Agency (ESA)

- Copernicus POD Quality Working Group,
  Member: Dettmering D.

European Geosciences Union (EGU)

- Geodesy Division,
  President: Schmidt M.

European Space Agency (ESA)

- Organizing Committee for the Coastal Altimetry Workshop,
  Member: Passaro M.
- Scientific Committee of "25 Years of Progress in Radar Altimetry Symposium",
  Member: Passaro M.

European Space Agency (ESA) / European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT)

- Sentinel-3 Validation Team, Altimetry sub-group,
  Member: Dettmering D.

European Union (EU)

- Coastal Waters Research Synergy Framework (CoReSyf) User Board,
  Member: Passaro M.

Forschungsgruppe Satellitengeodäsie (FGS)

- *Deputy Speaker: Seitz F.*

International Association of Geodesy (IAG)

- Commission 1, Sub-Commission 1.4: Interaction of celestial and terrestrial reference frames,
  Member: Seitz M.
- Commission 1, Working Group 1.1.1 Co-locations using Clocks and New Sensors,
  Member: Kwak Y.

- Commission 1, Working Group 1.3.1 Time dependent transformations between reference frames,
  Member: Sánchez L.
- Commission 1, Joint Working Group 1.1 Site Survey and Co-location,
  Member:Angermann D., Schmid R., Seitz M.
- Commission 1, Joint Working Group 1.3 Troposphere Ties,
  Member: Kwak Y.
- Commission 1, Working Group 1.4.1: Consistent Realization of ITRF, ICRF, and EOP,
  Chair: Seitz M.
- Commission 1 / ICCT Joint Study Group 0.22 Definition of next generation terrestrial reference frames,
  Member: Bloßfeld M., Seitz M.
- Commission 4, Sub-Commission 4.3 Atmosphere Remote Sensing,
  Chair: Schmidt M.
- Commission 4, Working Group 4.3.1 Real Time Ionosphere Monitoring,
  Member: Dettmering D., Erdogan E.
- Commission 4, Working Group 4.3.2 Ionosphere Predictions,
  Vice-Chair: Erdogan E.
- Commission 4, Working Group 4.3.5 Ionosphere Scintillations,
  Member: Schmidt M.
- Commission 4, Joint Working Group 4.3.3 Combination of Observation Techniques for Multi-dimensional Ionosphere Modelling,
  Member: Erdogan E., Schmidt M.
- Global Geodetic Observing System (GGOS) Bureau of Products and Standards,
  Director: Angermann D., Member: Gerstl M., Sánchez L.
- Global Geodetic Observing System (GGOS) Coordinating Board,
  Member: Angermann D., Sánchez L., Schmidt M.
- Global Geodetic Observing System (GGOS) Executive Committee,
  Member: Angermann D.
- Global Geodetic Observing System (GGOS) Focus Area Geodetic Space Weather Research,
  Chair: Schmidt M.
- Global Geodetic Observing System (GGOS) Focus Area Unified Height System,
  Chair: Sánchez L.
- Global Geodetic Observing System (GGOS) Joint Working Group on the Realization of the IHRS,
  Chair: Sánchez L.
- Global Geodetic Observing System (GGOS) Working Group on Performance Simulations and Architectural Trade-Offs (PLATO),
  Member: Bloßfeld M., Kehm A., Seitz M.
- ICCT Joint Study Group 0.19 Time series analysis in geodesy,
  Member: Schmidt M.

- ICCT Joint Study Group 0.20 Space weather and ionosphere,
  Member: Erdogan E., Schmidt M.
- ICCT Study Group 5: Fusion of multi-technique satellite geodetic data,
  Member: Bloßfeld M.
- Symposia Series,
  Assistant Editor-in-Chief: Sánchez L.
- Working Group for the establishment of the Global Geodetic Reference Frame (GGRF),
  Member: Angermann D., Sánchez L.

International Astronomical Union (IAU)

- Commission A.2, Rotation of the Earth,
  Vice-President: Seitz F.
- Division A Working Group: Third Realisation of International Celestial Reference Frame,
  Member: Seitz M.

International Earth Rotation and Reference Systems Service (IERS)

- Directing Board,
  Associate member: Angermann D., Bloßfeld M.
- ITRS Combination Centre,
  Chair: Seitz M., Member: Bloßfeld M.
- Working Group on SINEX Format,
  Member: Seitz M.
- Working Group on Site Coordinate Time Series Format,
  Member: Seitz M.

International DORIS Service (IDS)

- Governing Board,
  Member: Dettmering D.
- DORIS Analysis Working Group,
  Member: Rudenko S.
- Working Group on NRT DORIS data,
  Chair: Dettmering D., Member: Erdogan E., Schmidt M.

International GNSS Service (IGS)

- Governing Board,
  Member: Schmid R., Network Representative: Sánchez L.
- Antenna Working Group,
  Chair: Schmid R.
- GPS Tide Gauge Benchmark Monitoring - Working Group,
  Member: Sánchez L.
- Ionosphere Working Group,
  Member: Schmidt M.
- Regional Network Associate Analysis Centre for SIRGAS,
  Chair: Sanchez L.

International Laser Ranging Service (ILRS)

- Governing Board,
  Member: Müller H.
- Analysis Standing Committee,
  Member: Bloßfeld M., Müller H.
- Data Centre (EDC),
  Chair: Schwatke C., Member: Müller H.
- Data Formats and Procedures Standing Committee,
  Chair: Müller H., Member: Schwatke C.
- LARGE (LAser Ranging to GNSS s/c Experiment) Study Group,
  Member: Müller H.
- Networks and Engineering Standing Committee,
  Member: Schwatke C.
- Operations Centre (EDC),
  Chair: Schwatke C.
- Quality Control Board,
  Member: Müller H.
- Study Group on Data Format Update,
  Member: Schwatke C.
- Study Group on ILRS Software Library,
  Member: Schwatke C.

International VLBI Service for Geodesy and Astrometry (IVS)

- IVS Working Group on Satellite Observations with VLBI,
  Member: Kwak Y.
- Operational Analysis Centre,
  Member: Kwak Y., Schmid R.

International Service for the Geoid (ISG)

- *Scientific advisor: Sánchez L.*

International Union of Geodesy and Geophysics (IUGG)

- *Representative to the Panamerican Institute for Geodesy and History (PAIGH):
  Sánchez L.*

Sistema de Referencia Geocéntrico para las Américas (SIRGAS)

- Scientific Committee,
  Member: Sánchez L.
- SIRGAS Analysis Centre,
  Chair: Sánchez L.

United Nations Global Geospatial Information Management (UN-GGIM)

- Working Group for a Global Geodetic Reference Frame (GGRF),
  *IAG Representative for Key Area "Data Sharing and Development of Standards":
  Angermann D.*

4.3 Publications

Angermann D., Böhm J.: *IAG-IASPEI Joint Scientific Assembly 2017, Session G01: Reference Frames*. Zeitschrift für Geodäsie, Geoinformation und Landmanagement (zfv) 142 (6), 2017

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4.4 Posters and oral presentations

Angermann D.: *Status report on BPS activities*. GGOS Coordinating Board Meeting, Vienna, Austria, 2017

Angermann D.: *Overview of BPS activies, BPS Implementation Plan 2017-2018*. Bureau of Products and Standards Meeting, Vienna, Austria, 2017

Angermann D.: *Geodetic Reference Systems*. Delegation visit from the Chinese Academy of Sciences (CAS) to DGFI-TUM, Munich, Germany, 2017

Angermann D.: *Literature survey and review of IERS EOP determination*. PDR Meeting to ESA project "Independent generation of Earth orientation parameters", Munich, Germany, 2017

Angermann D., Bloßfeld M.: *Status Report for PN5a of FOR1503*. FOR1503 status seminar, Berlin, Germany, 2017

Angermann D., Bloßfeld M., Gerstl M., Kwak Y., Schmid R., Seitz M.: *Consistent realization of celestial and terrestrial reference frames*. Geodätische Woche 2017, Berlin, Germany, 2017

Angermann D., Gruber T., Gerstl M., Hugentobler U., Heinkelmann R., Sanchez L., Steigenberger P.: *Next steps after BPS inventory*. Unified Analysis Workshop, Paris, France, 2017

Angermann D., Gruber T., Gerstl M., Hugentobler U., Sanchez L., Heinkelmann R., Steigenberger P.: *The Bureau of Products and Standards and its key role within GGOS*. European Geosciences Union General Assembly, Vienna, Austria, 2017 (Poster)

Angermann D., Gruber T., Gerstl M., Hugentobler U., Sanchez L., Heinkelmann R., Steigenberger P.: *GGOS Bureau of Products and Standards*. IAG-IASPEI Joint Scientific Assembly 2017, Kobe, Japan, 2017 (Poster)

Angermann D., Gruber T., Gerstl M., Hugentobler U., Sanchez L., Heinkelmann R., Steigenberger P.: *Overview of BPS activities and future plans*. GGOS Days 2017, Vienna, Austria, 2017

Angermann D., Gruber T., Gerstl M., Hugentobler U., Sanchez L., Heinkelmann R., Steigenberger P.: *GGOS Bureau of Products and Standards: Recent activities and future plans*. IAG-IASPEI Joint Scientific Assembly 2017, Kobe, Japan, 2017

Benveniste J., Bonekamp H., Cipollini P., Dufau C., Miller L., Passaro M., Picot N., Strub T., Vandemark D., Vignudelli S., Wilkin J.: *An overview of recent progress in Coastal Altimetry and its synergies with modelling*. 5th GODAE OceanView Coastal Ocean and Shelf Seas Task Team (COSS-TT) International Coordination Meeting (COSS-ICM5), Breakwater Lodge, Cape Town, South Africa, 2017

Bloßfeld M.: *Introduction to the lecture on reference systems*. Information for Geodesy master students, Munich, Germany, 2018

Bloßfeld M.: *Scientific snapshots of SLR-related research performed at DGFI-TUM*. SLR splinter meeting, Bonn, Germany, 2017

Bloßfeld M., Angermann D., Seitz M.: *ITRS Combination Centre at DGFI-TUM*. ITRF error budget workshop, New Orleans, USA, 2017

Bloßfeld M., Angermann D., Seitz M.: *Report of the ITRS Combination Centre at DGFI-TUM*. IERS Directing Board meeting, New Orleans, USA, 2017

Bloßfeld M., Angermann D., Seitz M.: *Status Report for PN6b of FOR1503*. FOR1503 status seminar, Berlin, Germany, 2017

Bloßfeld M., Angermann D., Seitz M.: *DGFI-TUM analysis and scale investigations of the latest terrestrial reference frame realizations*. IAG-IASPEI Joint Assembly , Kobe, Japan, 2017

Bloßfeld M., Angermann D., Seitz M.: *Specific aspects of TRF/CRF computations at DGFI-TUM*. Unified Analysis Workshop, Paris, France, 2017

Bloßfeld M., Grahsl A., König D., Sosnica K., Krauss S., König R., Lemoine J.-M., Otsubo T.: *Combined SLR-derived gravity fields for EGSIEM*. EGSIEM Consortium Meeting, Bern, Switzerland, 2017

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Dettmering D.: *Multi-mission crossover analysis at DGFI-TUM*. Copernicus POD Quality Working Group Meeting, Darmstadt, Germany, 2017

Dettmering D.: *Relative calibration of Sentinel-3 by Multi-Mission Crossover Analysis (RECAS3)*. Sentinel-3 Validation Team Meeting, Frascati, Italy, 2017

Dettmering D., Schwatke C.: *Calibration and Validation of altimeter observations and models by means of global multi-mission crossover analysis*. 2017 Ocean Surface Topography Science Team (OSTST) meeting, Miami, FL, USA, 2017 (Poster)

Dettmering D., Schwatke C.: *Multi-mission cross-calibration: a prerequisite for climate studies based on satellite altimetry*. Satellite Geodesy for Climate Studies, IAG Workshop, Bonn, Germany, 2017

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Esselborn S., Rudenko S., Schöne T.: *Assessment of the orbit related sea level errors for TOPEX altimetry at seasonal to decadal time scales*. Ocean Surface Topography Science Team (OSTST) Meeting, Miami, Florida, USA, 2017

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Goss A., Erdogan E., Schmidt M., Garcia-Rigo A., Hernandéz-Pajares M., Lyu H., Nohutcu M.: *Advanced algorithms for ionosphere modelling in GNSS applications within the AUDITOR project*. European Geosciences Union General Assembly, Vienna, Austria, 2017

Göttl F., Bloßfeld M., Kehm A., Schmidt M., Seitz F.: *Determination of accuracy information for effective angular momentum functions derived from gravity field observations*. IAG-IASPEI Joint Scientific Assembly, 2017 (Poster)

Göttl F., Bloßfeld M., Kehm A., Schmidt M., Seitz F.: *Towards uncertainties in gravimetrically derived excitation mechanisms of Earth rotation: A case study of degree-1 Stokes coefficients and C20*. European Geosciences Union General Assembly, Vienna, Austria, 2017 (Poster)

Göttl F., Dettmering D., Müller F., Schwatke C.: *A new processing strategy for CryoSat-2 SAR data over lakes based on waveform classification, sub-waveform retracking and outlier rejection*. European Geosciences Union General Assembly, Vienna, Austria, 2017 (Poster)

Heinkelmann R., Angermann D., Gruber T., Gerstl M., Hugentobler U., Sanchez L., Steigenberger P.: *Interaction with IAU concerning standards*. GGOS Days 2017, Vienna, Austria, 2017

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Hinrichs J., Bothmer V., Mrotzek N., Venzmer M., Erdogan E., Dettmering D., Goss A., Schmidt M., Seitz F., Börger K., Brandert S., Görres, B., Kersten W.F.: *Impacts of Space Weather*

Effects on the Ionospheric Vertical Total Electron Content. European Geosciences Union General Assembly, Vienna, Austria, 2017 (Poster)

Hoque M., Garcia-Rigo A., Erdogan E., Cueto Santamaría M., Jakowski N., Berdermann J., Hernandez-Pajares M., Schmidt M., Wilken V.: *Ionosphere monitoring and forecast activities within the IAG working group "Ionosphere Prediction"*. European Geosciences Union General Assembly, Vienna, Austria, 2017 (Poster)

Hugentobler U., Seitz M., Angermann D., Bloßfeld M., Panafidina N., Rudenko S.: *PN 6: Consistent dynamic satellite reference frames and terrestrial geodetic datum parameters*. Status seminar DFG Research Unit FOR1503, Munich, Germany, 2017

Kehm A.: *ESA EOP model inventory: processing standards*. PDR Meeting to ESA project "Independent Generation of Earth orientation parameters", Munich, Germany, 2017

Kehm A., Bloßfeld M., Panafidina N., Rudenko S., Müller H., Angermann D., Hugentobler U., Seitz M.: *Konsistente Schätzung geodätischer Parameter mit Satellite Laser Ranging*. Geodätische Woche 2017, Berlin, 2017

Kehm A., Bloßfeld M., Seitz F.: *Evolution of the SLR ground and space segments and its potential for GGOS*. General Assembly 2017, Vienna, Austria, 2017 (Poster)

Kehm A., Bloßfeld M., Seitz F.: *E-GRASP and SLR: Impact of an additional orbit on SLR-derived low-degree Stokes coefficients*. E-GRASP science team meeting, Vienna, Austria, 2017

Kehm A., Bloßfeld M., Seitz F.: *Future evolution of the SLR ground and space segments and its impact on the estimation of TRF, EOP and Stokes coefficients*. GGOS PLATO standing commitee meeting, Vienna, Austria, 2017

Kehm A., Bloßfeld M., Seitz F.: *Future evolution of the SLR ground segment and its impact on the estimation of TRF and EOP*. IGOS Workshop, Wettzell, Germany, 2017

Krypiak-Gregorczyk A., Wielgosz P., Borkowski A., Schmidt M., Erdogan E., Goss A.: *Comparison of Ionospheric Vertical Total Electron Content modelling approaches using spline based representations*. European Geosciences Union General Assembly, Vienna, Austria, 2017 (Poster)

Kwak Y., Angermann D., Bloßfeld M., Gerstl M., Schmid R., Seitz M.: *Assessment of Common Adjustment of CRF, TRF, and EOP: Impact of EOP Combination Setups*. Journées des Systèmes de Référence et de la Rotation Terrestre, Alicante, Spain, 2017

Kwak Y., Angermann D., Bloßfeld M., Gerstl M., Schmid R., Seitz M. : *Common Adjustment of TRF, EOP and CRF for a Consistent Realization of Reference Systems*. European Geosciences Union General Assembly, Vienna, Austria, 2017 (Poster)

Kwak Y., Gerstl M., Bloßfeld M., Angermann D., Schmid R., Seitz M.: *DOGS-RI: new VLBI Analysis Software at DGFI-TUM*. 23rd Working Meeting of the European VLBI Group for Geodesy and Astrometry, Gothenburg, Sweden, 2017

Lago L.S., Saraceno M., Ruiz Etcheverry L.A., Passaro M., Oreiro F., D'Onofrio E.E., Gonzalez R.: *Improved Sea Surface Height from Satellite Altimetry in Coastal Zones: A Case Study in Southern Patagonia*. 10th Coastal Altimetry Workshop, Firenze, Italy, 2017 (Poster)

Legeais J.-F., Benveniste J., Cazenave A., Ablain M., Larnicol G., Meyssignac B., Johannessen J., Scharffenberg M., Timms G., Knudsen P., Andersen O., Cipollini P., Roca M., Rudenko S., Fernandes J., Balmaseda M., Quartly G., Fenoglio-Marc L., Ambrozio A., Restano M., Passaro M.: *Sea Level CCI: main achievements of the 6 years of the SLCCI project*. Sea Level CCI Phase II - 3rd annual review and final meeting, ESA/ESRIN, Frascati, Italy, 2017

Lemoine F.G., Moreaux G., Capdeville H., Lemoine J.M., Saunier J., Ferrage P., Soudarin L., Dettmering D., Ziebart M., Willis P., Michael P.: *The Status of DORIS in light of ITRF2014*. IAG-IASPEI Joint Scientific Assembly, Kobe, Japan, 2017

Lieb V., Schmidt M. : *Quasigeoidmodellierung in Norddeutschland*. BKG Internal Colloquium , Leipzig, Quasigeoidmodellierung in Norddeutschland, 2017

Lieb V., Schmidt M., Willberg M., and Pail R.: *Optimally combined regional geoid models for the realization of height systems in developing countries (ORG4Heights)*. European Geosciences Union General Assembly, Vienna, Austria, 2017 (Poster)

Männel B., Thaller D., Bloßfeld M.: *GGOS Standing Committee on Performance and Architectural Trade-Offs (PLATO) - Status report for the GGOS BNO meeting*. GGOS BNO meeting, New Orleans, USA, 2017

Matsuo K., Otsubo T., Bloßfeld M., Kehm A., Müller H.: *SLR contributions to time-variable gravity field and thermospheric neutral density estimates*. 2017 ILRS Technical Workshop, Riga, Latvia, 2017

Müller F.: *Using SAR Imaging to validate classification: Open Water detection by pixel based SAR image processing*. Extension and improvement of the Mean Sea Level estimation in the Arctic regions using space altimetry data, International Space Science Institute (ISSI), Bern, Switzerland, 2017

Müller F., Dettmering D., Bosch W.: *Satellite altimetry in sea ice regions - detecting open water for estimating sea surface heights*. AK-Treffen Polargeodäsie and Glaziologie, 2017

Müller F., Dettmering D., Bosch W.: *Classification: innovations in multi-mission unsupervised methods and use of Range Integrated Power for Delay-Doppler*. Extension and improvement of the Mean Sea Level estimation in the Arctic regions using space altimetry data, International Space Science Institute (ISSI), Bern, Switzerland, 2017

Müller F., Dettmering D., Bosch W.: *Variations in ocean currents, sea ice concentration, and sea surface temperature along the North-East coast of Greenland (NEG-OCEAN)*. Research stay, Alfred Wegener Institut, Helmoltz Centre for Polar and Marine Research, Bremerhaven, Germany, 2017

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Müller J., Pail R., Bloßfeld M.: *Standing Committee on Satellite Missions (CSM) - status report*. GGOS BNO meeting, New Orleans, USA, 2017

Otsubo T., Müller H., Schwatke C., Pavlis E.: *The ILRS Rapid Service Mail a tool to inform stations quickly about potential problem*. ILRS Technical Workshop 2017, 2017

Passaro M., Calafat F. M.: *ALES coastal processing applied to ERS: Extending the coastal sea level time series*. 10th Coastal Altimetry Workshop, Firenze, Italy, 2017

Passaro M., Calafat F.M.: *A 20-year coastal dataset in the North Sea and Mediterranean Sea*. WCRP/IOC Conference 2017: Regional Sea Level Changes and Coastal Impacts, New York, USA, 2017 (Poster)

Passaro M., Dettmering D.: *COSTA: DGFI-TUM's Along Track Sea Level Product for ERS - 2 and Envisat (1996 - 2010) in the Mediterranean Sea and in the North Sea*. Satellite Geodesy for Climate Studies, IAG Workshop, Bonn, Germany, 2017 (Poster)

Passaro M., Rose S.K., Andersen O.B., Benveniste J.: *Innovations for satellite altimetry processing in the Arctic Ocean: development and application of a new sea level record (1992-2016).* WCRP/IOC Conference 2017: Regional Sea Level Changes and Coastal Impacts , New York, USA, 2017 (Poster)

Passaro M., Rose S.K., Andersen O.B., Boergens E., Calafat F.M., Dettmering D., Benveniste J.: *ALES+: Adapting a homogenous ocean retracker for satellite altimetry to sea ice leads, coastal and inland waters.*. OSTST Meeting 2017, Miami, USA, 2017

Passaro M., Smith W., Schwatke C., Piccioni G., Dettmering D.: *Validation of a global dataset based on subwaveform retracking: improving the precision of pulse-limited satellite altimetry*. OSTST Meeting 2017, Miami, USA, 2017

Piccioni G., Dettmering D., Bosch W., Passaro M., Seitz F. : *Coastal improvements for tidal models: the benefit of ALES retracker*. Ocean Surface Topography Science Team (OSTST) Meeting, Miami, Florida, USA, 2017

Piccioni G., Dettmering D., Bosch W., Seitz F.: *Enhance Coastal Tide Modeling Using Cryosat-2: A Feasibility Study*. 10th Coastal Altimetry Workshop, 2017 (Poster)

Rose S.K., Andersen O.B., Passaro M., Benveniste J.: *An updated 26-year (1991-2017) sea level record from the Arctic Ocean*. European Geosciences Union General Assembly, Vienna, Austria, 2017

Rudenko S., Bloßfeld M., Müller H., Dettmering D., Angermann D., Kehm A.: *Validation of DTRF2014, ITRF2014 and JTRF2014 by precise orbit determination of SLR and altimetry satellites*. European Geosciences Union General Assembly, Vienna, Austria, 2017 (Poster)

Rudenko S., Bloßfeld M., Müller H., Dettmering D., Angermann D., Seitz M.: *Assessment of the new International Terrestrial Reference System realizations by precise orbit determination of SLR satellites*. Geodätische Woche 2017, Berlin, Germany, 2017

Rudenko S., Bloßfeld M., Müller H., Dettmering D., Angermann D., Seitz M.: *Assessment of the International Terrestrial Reference System 2014 realizations by precise orbit determination of SLR satellites*. Ocean Surface Topography Science Team (OSTST) Meeting, Miami, Florida, USA, 2017

Rudenko S., Passaro M., Bloßfeld M., Dettmering D., Angermann D., Seitz F.: *DGFI-TUM proposal for the ESA CCI+ project*. Sea Level CCI Phase II - 3rd annual review and final meeting, ESA/ESRIN, Frascati, Italy, 2017

Sánchez L.: *Kinematics of the SIRGAS Reference Frame*. Symposium SIRGAS2017, Mendoza, Argentina, 2017

Sánchez L.: *Advances in the implementation of the International Height Reference System (IHRS)*. Symposium SIRGAS2017, Mendoza, Argentina, 2017

Sánchez L.: *Recent activities of the IGS Regional Network Associate Analysis Centre for SIRGAS (IGS RNAAC SIRGAS)*. Symposium SIRGAS2017, Mendoza, Argentina, 2017

Sánchez L.: *GGOS Focus Area Unified Height System: Report, ongoing activities, outlook*. GGOS Days 2017, Vienna, Austria, 2017

Sánchez L., Čunderlík R., Mikula K., Minarechová Z., Dayoub N., Šíma Z., Vatrt V., Vojtíšková M.: *A conventional value for the geoid reference potential W0*. Unified Analysis Workshop 2017 (UAW2017), Paris, France, 2017

Sánchez L., Denker H., Pail R., Lieb V., Huang J., Roman D., Ågren J., Amos M., Ihde J., Barzaghi R., Sideris M., Oshchepkov I., Blitzkow D., Matos A.C.O.C., Piñon D., Avalos D., Freitas S.R.C., Luz R.: *A first approximation to the International Height Reference Frame (IHRF)*. Joint Scientific Assembly of the International Association of Geodesy and the International Association of Seismology and Physics of the Earth's Interior (IAG-IASPEI 2017), Kobe, Japan, 2017

Sánchez L., Drewes H.: *Crustal deformation and surface kinematics after the 2010 earthquakes in Latin America*. Joint Scientific Assembly of the International Association of Geodesy and the International Association of Seismology and Physics of the Earth's Interior (IAG-IASPEI 2017), Kobe, Japan, 2017

Sánchez L., Drewes H., Brunini C.: *Geodetic monitoring of the surface deformation in Latin America*. Strengthening Disaster Risk Reduction across the Americas: A Regional Summit on the Contribution of Earth Observations, Buenos Aires, Argentina, 2017

Sánchez L., Ihde J., Pail R., Gruber T., Barzaghi R., Marti U., Ågren J., Sideris M., Novák P.: *Towards a first realization of the International Height Reference System (IHRS)*. European Geosciences Union General Assembly, Vienna, Austria, 2017

Sánchez L. Sideris M.G.: *Vertical datum unification for the International Height Reference System (IHRS)*. European Geosciences Union General Assembly 2017, Vienna, Austria, 2017

Schmid R., Bloßfeld M., Kwak Y., Gerstl M., Angermann D.: *DGFI part of project PN 5: status report*. Status seminar DFG Research Unit FOR1503, Munich, 2017

Schmidt M.: *Combination of space-geodetic observation techniques for ionosphere modeling and space weather research*. VERA Colloquium, ETH, Zürich, Switzerland, 2017

Schmidt M.: *Geodetic Space Weather Monitoring by means of Ionosphere Modelling*. European Geosciences Union General Assembly, Vienna, Austria, 2017

Schmidt M.: *Geodetic Monitoring of the Ionosphere*. Workshop: From atmosphere to space weather, Potsdam, 2017

Schmidt M., Bloßfeld M., Erdogan E., Meraner A.: *Analysis of spatio-temporal structures of the thermospheric density*. European Geosciences Union General Assembly, Vienna, Austria, 2017 (Poster)

Schmidt M., Bloßfeld M., Rudenko S., Xiong C., Lühr H.: *Calibration of an empirical thermospheric model by using SLR observations to ANDE-Pollux*. SPP 1788 Dynamic Earth Colloquium, Bremen, Germany, 2017 (Poster)

Schmidt M., Bloßfeld M., Rudenko S., Xiong C., Lühr H.: *Calibration of empirical thermospheric models by using laser observations to near-Earth orbiting spherical satellites*. IAG-IASPEI Joint Scientific Assembly, Kobe, Japan, 2017 (Poster)

Schmidt M., Börger K.: *Focus Area on Geodetic Space Weather Research* . GGOS-Days 2017, Vienna, Austria, 2017

Schmidt M., Garcia-Rigo A., Erdogan E., Goss A., Roma-Dollase D., Hernandez-Pajares M.: *Assessment and comparisons of ionospheric vertical total electron content products*. IAG-IASPEI Joint Scientific Assembly, Kobe, Japan, 2017

Schmidt M., Garcia-Rigo A., Erdogan E., Goss A., Roma-Dollase D., Hernandez-Pajares M.: *Assessment and comparisons of ionospheric vertical total electron content products*. IAG-IASPEI Joint Scientific Assembly, Kobe, Japan, 2017

Schmidt M., Garcia-Rigo A., Erdogan E., Goss A., Roma-Dollase D., Hernandez-Pajares M. : *Assessment and comparisons of ionospheric vertical total electron content products* . IAG-IASPEI Joint Scientific Assembly, Kobe, Japan, 2017

Schmidt M., Goss A., Erdogan E., Dettmering D., Seitz F., Börger K., Brandert S., Görres B., Kersten W. F., Bothmer V., Hinrichs J., Mrotzek N.: *Global and regional high resolution VTEC Representations using B-Splines and Kalman filtering*. IAG-IASPEI Joint Scientific Assembly, Kobe, Japan, 2017

Schmidt M., Lieb V., Willberg M., Pail R.: *MRR and LSC - A mutual benefit for advanced regional gravity field modeling*. IAG-IASPEI Joint Scientific Assembly, Kobe, Japan, 2017

Schwatke C.: *Updated Procedure for "Station History Logs" and "Site Logs"*. ILRS Technical Workshop 2017, Riga, Latvia, 2017

Schwatke C, Dettmering D.: *DAHITI: Inland Water Levels from Space for Climate Studies*. IAG Workshop: Satellite Geodesy for Climate Studies, Bonn, Germany, 2017 (Poster)

Schwatke C., Dettmering D.: *Mission-Independent Classification of Altimeter Waveforms for Applications in the Open Ocean, at the Coastal Zone and Over Land*. 10th Coastal Altimetry Workshop, Florence, Italy, 2017

Seitz F.: *Geodetic Earth Observation from Space: Research Activities at the Deutsches Geodätisches Forschungsinstitut (DGFI-TUM)*. Delegation visit from the Chinese Academy of Sciences (CAS) to DGFI-TUM, Munich, 2017

Seitz F.: *Global and regional geometrical reference systems of highest accuracy realized at DGFI-TUM*. Scientists Meet Scientists - Wednesday Coffee Talk of the TUM Institute of Advanced Studies (TUM-IAS), Garching, 2017

Seitz M., Angermann D., Bloßfeld M.: *Report from the ITRF Combination Centre at DGFI-TUM*. IERS Directing Board meeting, Vienna, Austria, 2017

Smith W.H.F., Leuliette E.W., Passaro M., Quartly G., Cipollini P.: *Covariant errors in ocean retrackers evaluated using along-track cross-spectra*. OSTST Meeting 2017, Miami, USA, 2017

Sobhkhiz S., Alizadeh M., Schmidt M.: *Ionospheric scintillation detection based on GPS observations, a case study over Iran* . IAG-IASPEI Joint Scientific Assembly, Kobe, Japan, 2017 (Poster)

Willberg M., Lieb V., Pail R., and Schmidt M.: *Study of Least Squares Collocation and Multi-Resolution Representation for Regional Gravity Field Modelling*. European Geosciences Union General Assembly, Vienna, Austria, 2017

Zare S., Alizadeh M., Schmidt M.: *Ionospheric parameter determination using integrated space geodetic data (case study: Iran)* . IAG-IASPEI Joint Scientific Assembly, Kobe, Japan, 2017 (Poster)

4.5 Participation in meetings, symposia, conferences

2017-01-17 : **E-GRASP Science Proposal Team meeting, Zurich, Switzerland**
Bloßfeld M., Angermann D.

2017-01-19/20 : **EGSIEM Consortium general meeting, Bern, Switzerland**
Bloßfeld M.

2017-02-01 : **Scientists meet Scientists, Garching, Germany**
Seitz, F.

2017-02-03/04 : **Retreat of the Faculty of Civil, Geo and Environmental Engineering of the TUM, Herrsching, Germany**
Seitz, F.

2017-02-15/17 : **Sentinel-3 Validation Team Meeting, Frascati, Italy**
Dettmering D.

2017-02-16/17 : **Status seminar, DFG Research Unit FOR1503 Reference Systems, Munich, Germany**
Angermann D., Bloßfeld M., Gerstl M., Kwak Y., Panafidina N., Rudenko S., Schmid R.

2017-02-21/24 : **10th Coastal Altimetry Workshop, Florence, Italy**
Passaro M., Piccioni G., Schwatke C.

2017-02-23 : **Midterm Review Meeting, H2020 project Auditor , Munich, Germany**
Erdogan E., Goss A., Schmidt M.

2017-02-27/28 : **Sea Level CCI Phase II Annual Review #3 and Final Meeting, Frascati, Italy**
Passaro M., Rudenko S.

2017-03-09/10 : **Coordination Meeting for DFG RU GlobalCDA, Frankfurt/Main, Germany**
Dettmering D., Seitz F.

2017-03-20/24 : **First CryoSat North American science meeting, Banff, Canada**
Börgens E.

2017-03-28 : **GGRF and GGOS: Coordination Meeting, Frankfurt/Main, Germany**
Seitz, F.

2017-04-04 : **Annual meeting of DGK Section Geodesy, Darmstadt, Germany**
Seitz, F.

2017-04-22 : **ILRS Analysis Standing Committee Meeting, Vienna, Austria**
Müller H.

2017-04-22 : **GGOS Coordinating Board Meeting, Vienna, Austria**
Angermann D.

2017-04-23 : **IERS Directing Board Meeting, Vienna, Austria**
Angermann D.

2017-04-24/28 : **European Geosciences Union General Assembly 2017, Vienna, Austria**
Angermann D., Bloßfeld M., Erdogan E., Kehm A., Kwak Y., Müller F., Sánchez L., Schmidt M., Seitz F.

2017-04-26 : **E-GRASP/Eratosthenes Science Team meeting, Vienna, Austria**
Bloßfeld M., Kehm A.

2017-04-27 : **UN GGIM Working Group "GGRF" Meeting, Vienna, Austria**
Angermann D.

2017-04-27 : **Annual meeting of the GGOS Standing Commitee PLATO, Vienna, Austria**
Bloßfeld M., Kehm A.

2017-05-03/05 : **Extension and improvement of the Mean Sea Level estimation in the Arctic regions using space altimetry data, International Space Science Institute (ISSI), Bern, Switzerland**
Müller F., Passaro M.

2017-05-09 : **Copernicus POD Quality Working Group Meeting, Darmstadt, Germany (via WebEx)**
Dettmering D.

2017-05-12 : **Tagung des Arbeitskreises "Polargeodäsie und Glaziologie" der "Deutschen Gesellschaft für Polarforschung e.V.", Munich, Germany**
Dettmering D., Müller F.

2017-05-15/19 : **23rd European VLBI for Geodesy and Astrometry Working Meeting, Gothenburg, Sweden**
Kwak Y.

2017-05-16 : **Kick-off Meeting TIK, DLR , Bonn, Germany**
Lalgudi Gopalakrishnan G., Schmidt M.

2017-05-22/23 : **DORIS Analysis Working Group meeting (AWG), London, UK**
Dettmering D.

2017-05-24 : **IDS Governing Board Meeting, London, UK**
Dettmering D.

2017-05-30/31 : **Workshop: From atmosphere to space weather, GFZ, Potsdam, Germany**
Schmidt M.

2017-06-03 : **FGS Board Meeting, Munich, Germany**
Schmidt M., Seitz F.

2017-06-14/16 : **SPP 1788 Kolloquium, Bremen, Germany**
Schmidt M.

2017-06-17 : **IGOS Workshop, Wettzell, Germany**
Angermann D., Bloßfeld M., Glomsda M., Seitz F.

2017-06-19/23 : **Research stay, Alfred Wegener Institut, Helmoltz Centre for Polar and Marine Research, Bremerhaven, Deutschland**
Müller F.

2017-06-28/29 : **BKG Internal Colloquium, Leipzig, Germany**
Lieb V., Schmidt M.

2017-07-10/14 : **Unified Analysis Workshop, Paris, France**
Angermann D., Bloßfeld M.

2017-07-10/14 : **WCRP/IOC Conference 2017: Regional Sea Level Changes and Coastal Impacts, New York, USA**
Passaro M.

2017-07-11/12 : **SGI Workshop 2017, Berlin, Germany**
Erdogan E.

2017-07-18/20 : **Status Seminar of Project OPTIMAP, Munich, Germany**
Erdogan E., Dettmering D., Goss A., Lalgudi Gopalakrishnan G., Schmidt M., Seitz F.

2017-07-24 : **System Integration Review Meeting, H2020 project Auditor, Barcelona, Spain**
Erdogan E., Schmidt M.

2017-07-31/08-04 : **Joint Scientific Assembly of the International Association of Geodesy and the International Association of Seismology and Physics of the Earth's Interior (IAG-IASPEI 2017), Kobe, Japan**
Angermann D., Sánchez L., Schmidt M.

2017-09-19/21 : **IAG Workshop: Satellite Geodesy for Climate Studies, Bonn, Germany**
Dettmering D.

2017-09-26 : **Status seminar, DFG Research Unit FOR1503 Reference Systems, Berlin, Germany**
Angermann D., Bloßfeld M., Rudenko S.

2017-09-26/28 : **INTERGEO/Geodätische Woche, DVW, Berlin, Germany**
Seitz F., Angermann D., Bloßfeld M., Kehm A., Rudenko S.

2017-09-30 : **FGS Board Meeting, Munich, Germany**
Schmidt M., Seitz F.

2017-10-01 : **ILRS Analysis Standing Committee Meeting, Riga, Latvia**
Müller, H. Schwatke, C.

2017-10-02/05 : **ILRS Technical Workshop, Riga, Latvia**
Müller, H. Schwatke, C.

2017-10-10 : **Review meeting DFG RU GlobalCDA, Bonn, Germany**
Dettmering D., Seitz F.

2017-10-23/27 : **2017 Ocean Surface Topography Science Team (OSTST) meeting, Miami, FL, USA**
Dettmering D., Passaro M., Piccioni G., Rudenko S.

2017-10-31/11-02 : **GGOS Days 2017, Vienna, Austria**
Angermann D., Sánchez L., Schmidt M.

2017-11-07/08 : **CryoSat Scientific Expert Meeting, ESA/ ESRIN, Frascati, Italy**
Passaro M.

2017-11-08/10 : **DGK Annual Meeting, Munich, Germany**
Seitz, F.

2017-11-14/16 : **Status Seminar of Project OPTIMAP, Göttingen, Germany**
Erdogan E., Goss A., Schmidt M., Seitz F.

2017-11-23 : **VERA-Kolloquium ETH, Zürich, Switzerland**
Schmidt M.

2017-11-27/12-02 : **Symposium SIRGAS2017, Mendoza, Argentina**
Sánchez L.

2017-12-09 : **IERS DB Meeting, New Orleans, USA**
Bloßfeld M.

2017-12-11/15 : **American Geophysical Union (AGU) Fall Meeting, New Orleans, USA**
Bloßfeld M.

2017-12-14 : **GGOS BNO Meeting, New Orleans, USA**
Bloßfeld M.

2017-12-14 : **ITRF Error budget workshop, New Orleans, USA**
Bloßfeld M.

5 Projects

A large part of DGFI-TUM's research activities is financed through third-party funds from various sources. Funding of the following projects is gratefully acknowledged (in alphabetic order):

AUDITOR Advanced multi-constellation EGNSS Augmentation and Monitoring Network (EU Horizon2020)

CIEROT Combination of space geodetic observations for the determination of mass transports in the cryosphere and their impact on Earth rotation (DFG)

DAAD Thematic Network Modern Geodetic Space Techniques for Global Change Monitoring (DAAD)

DIGERATI Direct geocentric realisation of the American reference frame by combination of geodetic observation techniques (DFG)

ESA-EOP Independent generation of Earth Orientation Parameters (ESA)

FOR 1503, PN5-2 Consistent celestial and terrestrial reference frames by improved modeling and combination-2 (DFG)

FOR 1503, PN6-1 Consistent dynamic satellite reference frames and terrestrial geodetic datum parameters-1 (DFG)

FOR 1503, PN6-2 Consistent dynamic satellite reference frames and terrestrial geodetic datum parameters-2 (DFG)

NEG-OCEAN Variations in ocean currents, sea ice concentration and sea surface temperature along the North-East coast of Greenland (DFG)

OPTIMAP Operational Tool for Ionospheric Mapping And Prediction (ZGeoBw)

ORG4Heights Optimally combined regional geoid models for the realization of height systems in developing countries (DFG)

REWAP Monitoring and Prediction of Regional Water Availability for Agricultural Production under the Influence of Climate Anomalies and Weather Extremes (DFG/IGSSE)

SPP 1788, INSIGHT Interactions of low-orbiting satellites with the surrounding ionosphere and thermosphere (DFG)

SLCCI Sea Level Climate Change Initiative (ESA)

SWARM+Innovations SLIM Swarm Magnetic Gradients for Lithospheric Modelling (ESA)

UHR-GravDat Consistent estimate of ultra-high resolution Earth surface gravity data (DFG)

TIK Entwicklung eines operationellen Prototyps zur Bestimmung der thermosphärischen Dichte auf Basis eines Thermosphären-Ionosphären Kopplungsmodells (BMWi/DLR)

WLDYN Assessing the spatiotemporal dynamics of water volumes in large wetlands and lakes by combining remote sensing with macro-scale hydrological modelling (DFG)

6 Personnel

6.1 Lectures and courses at universities

Bloßfeld M. Lecture "Realisierung und Anwendungen globaler geodätischer Referenzsysteme", TUM, SS 2017

Bloßfeld M. Lecture "Earth System Dynamics", TUM, WS 2016/2017 and WS 2017/18

Bosch W. and Passaro M. Lecture "Oceanography and Satellite Altimetry", TUM, WS 2016/17 and WS 2017/18

Dettmering D. Lecture "Hydrogeodesy: Monitoring surface waters from space", TUM, WS 2017/18

Sánchez L. Lecture "Vertiefende Aspekte der Höhensysteme", TUM, WS 2016/17 and WS 2017/18

Schmidt M. Lecture "Numerical Modelling", TUM, WS 2016/17 and WS 2017/18

Schmidt M. Lecture "Numerische Methoden in der Satellitengeodäsie", TUM, SS 2017

Schmidt M. Lecture "Höhere Geodäsie/Ausgleichsrechnung", HCU, SS 2017

Schmidt M. Lecture "Ionosphärenmonitoring und -modellierung", TUM, WS 2016/17 and WS 2017/18

Seitz F. Lecture "Earth System Dynamics", TUM, WS 2016/17 and WS 2017/18

Seitz F. Lecture "Seminar ESPACE", TUM, SS 2017

Seitz F. Doktorandenseminar des Deutschen Geodätischen Forschungsinstituts, TUM, WS 2016/17, SS 2017 and WS 2017/18

Seitz F. Lecture "Erdrotation", TUM, WS 2016/17 and WS 2017/18

6.2 Lectures at seminars and schools

Angermann D. : Lecture "Geodäsie - Die Vermessung der Erde im Wandel der Zeit". Seminarvortrag für die Oberstufe Q11, Sebastian Finsterwalder Gymnasium, Rosenheim, Germany, 2017-01-09

Passaro M. : Lecture "Overview of Altimetry Corrections". European Space Agency SAR Altimetry Training Course, Florence, Italy, 2017-02-21/24

Angermann D. : Lecture "Geodäsie - Die Vermessung der Erde im Wandel der Zeit". Vortragsreihe am Gymnasium Raubling, Raubling, Germany, 2017-10-10

Angermann D. : Lecture "Realisierung des Globalen Geodätischen Referenzsystems (ITRS) am DGFI-TUM - Herausforderungen und gesellschaftliche Relevanz". Autumn School Geodesy and Geoinformation, Bayerische Vermessungsverwaltung, Munich, Germany, 2017-12-06

Dettmering D. : Lecture "Satelliten-Altimetrie: Bestimmung von Wasserständen aus dem Weltraum - vom Ozean bis zur Donau". Autumn School Geodesy and Geoinformation, Bayerische Vermessungsverwaltung, Munich, Germany, 2017-12-06

Seitz F. : Lecture “Hochgenaue Vermessung der Erde aus dem Weltraum – Aktuelle Arbeiten am Deutschen Geodätischen Forschungsinstitut”. Autumn School Geodesy and Geoinformation, Bayerische Vermessungsverwaltung, Munich, Germany, 2017-12-06

6.3 Thesis supervision

Master and Bachelor Theses

Seitz F., Sánchez L. : Master Thesis Sokolov A., TUM: Deformation model of the Alpine region inferred from GNSS observations. 2017-03-02

Schmidt M. : Master Thesis Mason S., TUM: Adaptive modeling of the Vertical Total Electron Content of the Earth’s ionosphere. 2017-09-25

Seitz F., Dettmering D. : Master Thesis Pircklen R., TUM: Using ICESat laser altimeter data for the detection of open water returns in sea ice regions. 2017-09-29

Seitz F., Passaro M. : Master Thesis Nadzir Z., TUM: Coastal sea state bias: correcting coastal sea level by studying the relation between wind, waves and the radar signals. 2017-11-21

Seitz F., Dettmering D. : Master Thesis Wynne A., TUM: Lead detection in polar oceans using Cryosat-2 SAR observations. 2017-12-11

Schwatke C. (co-supervisor) : Bachelor Thesis Scherer D., Munich University of Applied Sciences (prepared in co-operation with DGFI-TUM): Automated Extraction of Time-Variable Water Surfaces with Cloud-Based Google Earth Engine. 2017-04-21

Doctoral Theses

Schmidt M. (supervisor)**:** Doctoral Thesis Liang W., TUM: A regional physics-motivated electron density model of the ionosphere. 2017-01-25

Seitz F. (supervisor)**:** Doctoral Thesis Singh A., TUM: Dynamics of water mass variations in lake/reservoir dominated regions from multi-sensor Earth observation data and hydrological model outputs. 2017-03-14

Seitz F. (co-supervisor)**:** Doctoral Thesis Roohi S., University of Stuttgart: Performance evaluation of different satellite radar altimetry missions for monitoring inland water bodies. 2017-03-31

6.4 Conferral of Doctorates

Liang W. : *Title*: A regional physics-motivated electron density model of the ionosphere. *Supervisors*: Prof. Dr.-Ing. M. Schmidt (TUM), Prof. Dr. U. Hugentobler (TUM), Prof. Dr. C. Brunini (Universidad Nacional de La Plata, Argentina). *Day of defense*: 2017-01-25. *Institution*: TUM

Singh A. : *Title*: Dynamics of water mass variations in lake/reservoir dominated regions from multi-sensor Earth observation data and hydrological model outputs. *Supervisors*: Prof. Dr.-Ing. F. Seitz (TUM), Prof. Dr. A. Güntner (GFZ Potsdam), Prof. Dr.-Ing. M. Disse (TUM) *Day of defense*: 2017-03-14 *Institution*: TUM