DEUTSCHE GEODÄTISCHE KOMMISSION

bei der Bayerischen Akademie der Wissenschaften

Reihe B | Angewandte Geodäsie | Heft Nr. 315

NATIONAL REPORT
OF THE FEDERAL REPUBLIC OF GERMANY
ON THE GEODETIC ACTIVITIES
IN THE YEARS 2003 – 2007

XXIV General Assembly
of the International Union for Geodesy and Geophysics (IUGG)
2007 in Perugia/Italy

edited by
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Adresse des Herausgebers /
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Deutsche Geodätische Kommission
Alfons-Goppel-Straße 11
D – 80 539 München
Telefon +49 - (0)89 - 23 031 -0 / -1113
Telefax +49 - (0)89 - 23 031 -1283 / -1100
E-mail hornik@dgfi.badw.de
Internet http://dgk.badw.de

Adressen der Herausgeber dieses Bandes / Addresses of the editors of this volume

Univ. Prof. Dr.-Ing. Jürgen Müller
Institut für Erdmessung
Leibniz Universität Hannover
Schneiderberg 50
D - 30167 Hannover
Fax: +49 - 511 - 762 - 40 06
Tel.: +49 - 511 - 762 - 33 62
E-mail: mueller@ife.uni-hannover.de

Dipl.-Ing. Helmut Hornik
Deutsche Geodätische Kommission
Alfons-Goppel-Straße 11
D - 80539 München
Fax: +49 - 89 - 2 30 31 -12 83 / -11 00
Tel.: +49 - 89 - 2 30 31 11 13
E-mail: hornik@dgfi.badw.de

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Foreword

The XXIV General Assembly of the International Union of Geodesy and Geophysics (IUGG) will take place in Perugia/Italy from July 2 to July 13, 2007. It is a good tradition to take this opportunity for a review of the progress made in the fields of geodesy and geophysics within the period from 2003 to 2007. When the preparation of the National report has been discussed by the members of the German Geodetic Commission there was considerable doubt whether it should still be provided in printed form or rather distributed only electronically. The commission came to the conclusion that a printed documentation is still appropriate and it decided to provide a printed and an electronic version. We hope that the present report offers a useful overview of the geodetic research that has taken place in Germany during the past four years and that, in particular for the younger colleagues, it gives some ideas for future research.

The past four years were of great importance, to German geodesy in particular and to international geodesy in general.

Geodetic measurement techniques have meanwhile attained a level of precision and reliability that make them important tools for science and application not conceivable in previous times. Geodetic space techniques deliver global data sets that turn out to be of high relevance for the understanding of the current changes in our Earth system. It can also be observed that geodesy is more and more concerned with measuring temporal changes; whether it be plate motion, isostatic mass adjustment, ice motion, sea level change or temporal variations of the Earth's gravity field due to deglaciation, atmospheric and ocean mass transports and the global water cycle or the variable rotation of Earth reflecting global effects of mass variations and motion in all Earth components including the Earth deep interior. However it is not only Earth sciences; applications extend from civil engineering, disaster management, navigation, time synchronisation to planetology and fundamental physics.

In Germany a large part of research concentrated on the analysis of data from the on-going and very successful satellite missions CHAMP and GRACE, and on the preparation of the gravity gradiometric satellite mission GOCE. As important are the studies concerned with Earth rotation analysis, the preparations for GALILEO, optimization of the use of GNSS, and research towards the realization of the Global Geodetic Observing System (GGOS). This research has been funded in part by the Federal Ministry of Education and Research in its special Geotechnologies programme within the theme "Observation of System Earth from Space" and by the German Research Foundation (DFG) in particular with the research unit FOR 584 "Earth Rotation and Global Dynamic Processes" and with the priority program SPP-1257 "Mass Transport and Mass Distribution in the Earth System".

This National Report is arranged according to the new structure of IAG. The extensive contributions of Germany to the various IAG Services is described within the individual commission reports, except the work for the International Bibliographic Service (IBS) which is presented in a seperate report at the end of this volume.

The German Geodetic Commission acknowledges very much the work of all colleagues who contributed and who helped to coordinate this report. Our special thanks go to the two editors Jürgen Müller and Helmut Hornik for their excellent work in preparing this report.

München, 21 May 2007

Reiner Rummel
permanent secretary of
the German Geodetic Commission (DGK)

Contents

COMMISSION 1

REFERENCE FRAMES

Overview and Highlights

H. DREWES[1]

Overview

The activities of German scientists and institutions in the scientific research related to reference frames shall be highlighted according to the structure of the corresponding IAG Commission 1, which is divided into four Sub-commissions, two Inter-commission Projects, and two Inter-commission Study Groups:

- SC1.1 Coordination of Space Techniques,
- SC1.2 Global Reference Frames,
- SC1.3 Regional Reference Frames,
- SC1.4 Interaction of Celestial and Terrestrial Reference Frames,
- IC-P1.1 Satellite Altimetry,
- IC-P1.2 Vertical Reference Frames,
- IC-SG1.1 Vertical Reference Frames,
- IC-SG1.2 Use of GNSS for Reference Frames.

German scientists participated in all of these entities with basic research, developments of methodologies and software, and education. The investigations included theoretical, observational, analytical and product generating activities. They also held positions as Commission officers: HERMANN DREWES was the President of Commission 1, MARKUS ROTHACHER acted as the President of SC1.1, WOLFGANG BOSCH chaired the IC-P1.1, JOHANNES IHDE the IC-P1.2, and MICHAEL SCHMIDT the IC-SG1.1. Many scientists were active in the various working groups of the sub-commissions and projects.

The Commission's work is closely connected with the IAG services dealing with reference frames:

- International Earth Rotation and Reference Systems Service (IERS),
- International GNSS Service (IGS),
- International Laser Ranging Service (ILRS),
- International VLBI Service for Geodesy and Astrometry (IVS),
- International DORIS Service (IDS).
- International Altimetry Service (IAS, under development).

There was an intensive participation of German scientists and institutions in these services, also holding superior positions: BERND RICHTER as the Director of the IERS Central Bureau, MARKUS ROTHACHER as the IERS analysis coordinator, JOHN DOW as the President and GERD GENDT as the analysis coordinator of the IGS, WOLFGANG SCHLÜTER as the President and AXEL NOTHNAGEL as the analysis coordinator of the IVS. Other German scientists acted as chairs of Service's analysis (AC), combination (CC), data (DC) or operating centres (OC) which were conducted by

- Bayerische Kommission für die Internationale Erdmessung (BEK) in the IGS (AC for Europe),
- Bundesamt für Kartographie und Geodäsie (BKG) in IGS (AC and DC for Europe), ILRS (AC), and IVS (DC and AC),
- Deutsches Geodätisches Forschungsinstitut (DGFI) in IERS (ITRS CC), IGS (DC and AC for Latin America), ILRS (AC, CC and DC) and IVS (AC),
- Geodätisches Institut, Universität Bonn, (GIUB) in IVS (AC, OC and correlator),
- GeoForschungsZentrum Potsdam (GFZ) in IGS (AC) and ILRS (AC),
- Institut für Erdmessung, Universität Hannover (IfE) in ILRS (LLR),
- European Space Operations Centre (ESOC), Darmstadt, in IGS (AC).

These institutions also operated a large number of observation stations (GPS, SLR and VLBI) for the maintenance of global and regional reference frames, above all the Fundamental Station Wettzell (Germany) and the Transportable Integrated Geodetic Observatory (TIGO) in Concepción (Chile) of BKG. Others are the SLR station in Potsdam (GFZ), the VLBI station in O'Higgins (Antarctica, BKG) and many GPS stations of BEK, BKG, DGFI, GFZ all over the world.

Highlights

The most important investigations in the field of SC1.1 *"Coordination of space techniques"* were those done for the combination of the different observation types (GPS, SLR, VLBI, DORIS). Major activities were the participation in international projects, such as the IERS Combination Pilot Project. The project "Integration of space geodetic techniques as the basis for a Global Geodetic-Geophysical Observing System (GGOS-D)", financed by the German Bundesministerium für Bildung und Forschung (BMBF) is to study a rigorous combination with different approaches and software. Exactly identical constants, models and parameters are used for the analysis in all techniques. Other projects were the comparison and combination of precise orbits derived from different space techniques, in particular studies in low Earth orbiting satellites (LEOS) and the

[1] Hermann Drewes: Deutsches Geodätisches Forschungsinstitut (DGFI), Alfons-Goppel-Str. 11, D-80539 München, Germany, Tel. +49 - 89 - 23031-1106, Fax +49 - 89 - 23031 1240, e-mail drewes@dgfi.badw.de

interaction and consistency between the ITRF, EOP and gravity field.

The dominating activity with respect to SC1.2 "*Global Reference Frames"* were the investigations for and the computation of the International Terrestrial Reference Frame 2005 (ITRF2005) where several German scientists and institutions participated. The mathematical approaches for combining the observation results of the different techniques were intensively studied. Input data for the ITRF2005 were epoch (weekly or session-wise) station coordinates and daily Earth orientation parameters (EOP). These were provided as unique combined solutions by the techniques' services, in Germany by GIUB for VLBI and (as a backup solution) by DGFI for SLR. The combination of all the epoch solutions over a time span of more than twenty years was done at DGFI as one of the ITRS Combination Centres. The results were inter-changed and compared with the other Combination Centre at IGN, Paris. The final solution of ITRF2005 was released in October 2006.

In *SC 1.3 "Regional Reference Frames"* there were several German activities in Europe (EUREF), Latin America (SIRGAS), Antarctica (SCAR) and Africa (AFREF), all done within the IGS. BEK and BKG concentrated on EUREF, DGFI on SIRGAS, and the Institut für Planetare Geodäsie, Technische Universität Dresden (IPGD) on the Antarctic reference frame. Weekly station coordinate solutions (as loosely constrained normal equations) are provided for EUREF and SIRGAS. These are delivered to the IGS Analysis Centres for global combination. DGFI also provides weekly station coordinates consistent with the ITRF for users in Latin America. In Antarctica there are repeated observation campaigns, which are periodically combined and adjusted. AFREF is still in development; there were several meetings with German participation, where plans for establishing an African reference frame were discussed.

The *SC1.4 "Interaction of Celestial and Terrestrial Reference Frames"* works strongly towards the realization of a new ICRF. There were several studies concerning the theoretical aspects of the ICRF after the new precession model of the International Astronomical Union (IAU2000) and the systematic effects affecting the ICRF determination. A joint Working Group of IERS (including IVS) and IAU was established with German participation to compute a new ICRF in a common adjustment with the ITRF, EOP, and precession/nutation parameters. Several test computations were done at DGFI showing the improvements with respect to the nearly ten years old ICRF-Ext. 1.

The *IC-P1.1 "Satellite Altimetry"* has the primary objectives to identify the scientific requirements for a precise, long time series of consistent altimeter observations and to initiate the establishment of an International Altimeter Service for such a task. A planning group (IAS-PG) was installed under the chairmanship of WOLFGANG BOSCH. As a first result, a call for an IAS Integrating Office was released in January 2007.

Main activities of *IC-P1.2 "Vertical Reference Frames"* were to elaborate a proposal for the definition and realization of a global vertical reference system and the unification of regional (continental) height systems, which included the computation of a global W_0 value from sea surface and gravity field models. Other activities were the European Vertical Reference System (EVRS) and the re-measurement of the German First Order Levelling Network (DHHN).

The *IC-SG1.1 Ionosphere Modelling and Analysis* shall study the methodology to improve the parameters of existing physical ionosphere models (e.g., NeQuick, IRI) by geodetic observations (e.g., two-frequency GPS and Satellite Altimetry data). The parameters for geodetic use (e.g., TEC) can then be derived from such a model. There was a close cooperation with scientists from the International Centre for Theoretical Physics, Trieste, Italy and the Goddard Space Flight Centre, Greenbelt, USA, with a very promising progress.

All the activities in the *IC-SG1.2 "Use of GNSS for Reference Frames"* are performed in very close cooperation with the IGS. Topics are the integration of GPS and GLONASS data, where several German scientists did extensive studies, and the future adoption of the Galileo observations. There was also a significant German contribution to the Galileo Geodesy Service Provider (GGSP) project (BKG and GFZ).

A very important highlight of German activities in Commission 1 was the IAG Symposium *"Geodetic Reference Frames (GRF2006)"* organized by DGFI and held in October 2006 in Munich. More than 160 participants discussed in more than 100 presentations for one week all the topics dealt with in the Commission. A full day was spent for joint sessions with the XXIII Congress of the Fédération Internationale des Géomètres (FIG) and the German INTERGEO Congress, where mainly geodesists and engineers from practice are participating, thus offering the oportunity for direct scientific transfer.

Combination of Space Geodetic Techniques

M. ROTHACHER[1]

Introduction

The combination and integration of the data of the various space geodetic techniques like VLBI, SLR/LLR, GNSS, and DORIS but also the satellite missions is an important challenge of our time. The large variety of sensors should be integrated into one Global Geodetic Observing System (GGOS) that appears to the outside world as one large and complex "instrument" with the goal to monitor the processes in the Earth system. Because of the individual strengths and weaknesses of the observation techniques, it is a necessity to make use of their complementarity and to combine them in order to obtain consistent and highly accurate results. It is also clear that only the use of different, partially redundant techniques allows it to differ between technique-specific systematic biases and genuine geodynamic/geophysical signals and, thus, to make fast progress.

A very important aspect in the combination of different techniques is co-location. The co-location of different and complementary instruments is crucial for several reasons:

- Without co-location sites and highly accurate local tie information, it is impossible to establish a unique and common global reference frame for all major space geodetic techniques (e.g. for sea level monitoring).
- Co-location sites allow the comparison, validation and combination of estimated parameters common to more than one technique. The comparison is crucial for the detection of technique-specific biases and the combination of common parameters strengthens the solutions.
- Complementary observation techniques may be the only way to separate different processes taking place in the Earth system.

Both, co-location at the ground and co-location on satellites should be considered.

Intra-technique and Inter-Technique Combinations

Routine combination activities have been built up over the last few years and take place at a few institutions in Germany. In fact, Germany has an official intra-technique combination center for each of the space geodetic techniques (VLBI, SLR, GNSS) except for DORIS: DGFI (Deutsches Geodätisches Forschungsinstitut) is one of two intra-technique combination centers of the International Laser Ranging Service (ILRS) that is routinely combining the weekly solutions of the individual ILRS analysis centers to produce – together with ASI, the primary combination center – the official ILRS weekly products. At the Institute for Geodesy and Geoinformation (IGG) at the University of Bonn the combination of the individual weekly VLBI solutions is performed based on solutions delivered in SINEX files. Finally, at the GeoForschungsZentrum (GFZ) in Potsdam the IGS combined products (satellite orbits and satellite clocks) are generated. It should also be mentioned that, at present, the Analysis Coordinators of the IERS (MARKUS ROTHACHER), the IGS (GERD GENDT), and the IVS (AXEL NOTHNAGEL) are located in Germany. Inter-technique combinations are not yet done on a routine basis, but considerable know-how exists at DGFI as one of the ITRF Combination Centers (see Section "Terrestrial Reference Frames" in this volume for more details) and at GFZ. Most of the combination work has been done in the framework of the Geotechnologien projects (see below) and the new DFG Research Group "Earth Rotation and Geophysical Processes" (see the Section on "GGOS" in this report for more information about these major research programs).

Geotechnologien Project "GGOS-D"

GGOS-D (Integration of Space Geodetic Techniques as the Basis for a Global Geodetic-Geophysical Observing System) is probably the most important project in Germany concerning the combination of space geodetic techniques and therefore it is briefly described here. This project is funded by the Federal Ministry of Education and Research (BMBF). The participating institutions are GFZ, BKG (Bundesamt für Kartographie und Geodäsie), DGFI and IGG. The project is organized similar to a small "IERS", i.e., for each of the space geodetic techniques (VLBI, SLR, GPS, except DORIS) two fully reprocessed solutions (weekly SINEX files) are generated covering the entire data span of the observation techniques, using, in each case, two different software packages. These homogeneous series are then combined as rigorously as possible, first on the intra- then on the inter-technique level. In some aspects to be mentioned here, this project goes far beyond present international activities:

- Strict use of common standards concerning geodetic/geophysical models and the type of parameterization for all participating software packages – Inclusion of Low Earth Orbiters (CHAMP, GRACE, ...) and altimetry in addition to the space techniques SLR, VLBI, and GPS.
- Increase of the parameter space to be combined to link, for the first time, geometry, Earth rotation, gravity field and sea surface.

[1] Markus Rothacher: GeoForschungsZentrum Potsdam (GFZ), Department 1 Geodesy & Remote Sensing, Telegrafenberg A 17, D - 14473 Potsdam, Germany, Tel. +49 - 331 288 1100, Fax +49 - 331 288 1111, e-mail rothacher@gfz-potsdam.de

- Combination of additional parameters, namely quasar coordinates, nutation offsets and rates, troposphere zenith delays and gradients, and low degree spherical harmonic coefficients of the Earth's gravity field.
- Higher temporal resolution for some of the parameter types (not only weekly, but also daily solutions; sub-daily resolution of Earth rotation parameters).

Presently, the second iteration of solutions is produced and will subsequently be combined and interpreted.

So far major research aspects have been:

- Rigorous combination of site coordinates and EOP.
- Comparison and combination of troposphere parameters from GPS and VLBI.
- Importance of tropospheric local ties between GPS and VLBI.
- Combination of UT1 from VLBI and length of day from satellite techniques (GPS, SLR).
- Combination of nutation offsets (VLBI) and rates (GPS, SLR).
- Intensive studies of the local tie discrepancies between techniques.
- Homogeneous multi-year solutions of the techniques.
- Impact of systematic effects on the comparison/combination results like GPS receiver and satellite phase center variations, troposphere mapping functions, higher-order ionospheric corrections, etc.

Details may be found in the literature given at the end of this chapter.

Combination on the Observation Level

Combination on the level of the individual observations certainly is one of the challenging goals. To be able to do this, a software package has to developed that allows the processing of all the major observation types. In Germany, in the last few years, two software packages have been, step by step, modified in this direction: the Bernese GPS Software – in a joint effort of the TU Munich and the Astronomical Institute, University of Berne – has been modified to allow the processing of SLR data to GNSS satellites, to Lageos-type satellites and to Low Earth Orbiters and to allow the processing of VLBI data. Some work is also under way to add DORIS to the set of observables. The second package is the EPOS software of GFZ, where the processing of SLR, PRARE, GPS, altimetry, K-band, etc. data is possible. These capabilities are used to generate big global solutions of the GPS ground network, the SLR network and the LEOs CHAMP and GRACE in one step, correctly taking into account all correlations. First results are very encouraging. Solutions over longer time periods are now produced within the GGOS-D project.

Future Activities

One of the future goals will be to also integrate Lunar Laser Ranging solutions generated at the Institut für Erdmessung (IfE) in Hannover into the combination framework established by GGOS-D. One of the major challenges will then be, to go for a fully consistent combination of the geometric parameters with the full set of gravity field coefficients from CHAMP, GRACE and GOCE. On the long run, the integration of altimetry data and the data of superconducting and absolute gravimeters will be a additional challenges for the future. Finally, the combination of all common parameters of the space geodetic techniques will have to be followed by an integrated modelling of the variations in the Earth deformation, in Earth rotation and in the Earth gravity field. First attempts in this direction have been undertaken by DGFI (Earth rotation model of FLORIAN SEITZ) and the ocean-atmosphere-hydrology model by MAIK THOMAS at the TU Dresden.

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For further references see also section “Terrestrial Reference Frames” in this volume, p.17.

Celestial Reference Frames & Interaction with Terrestrial Reference Frames

V. TESMER[1]

Introduction

In geodesy, there are two types of celestial reference frames: (1) positions of extragalactic objects and (2) dynamic realizations by ephemeris (positions and velocities or orbital elements) of the planets, the moon and artificial earth orbiting satellites. The first ones are often called inertial, the second ones quasi inertial (see SCHUH et al., 2003). While satellite orbits are in general discussed in Commission 4 "Satellite Orbit Modelling", this chapter concentrates on (quasi) inertial frames as such and their interaction with terrestrial reference frames.

Towards ICRF2

In January 1998, the VLBI-determined ICRF (608 radio positions of extragalactic objects) replaced the optical FK5 as the celestial reference frame. Since then, it was extended twice, 1999 by 59 (ICRF-Ext1) and 2002 by 50 sources (ICRF-Ext2). To keep the ICRF homogeneous throughout the extensions, the same VLBI analysis setup was kept as used for the first solution in 1995. With continued applicable VLBI observations and improvements in analysis a better realization of the ICRF is now possible and an even better realization is feasible in the foreseeable future. So the IAU, the IERS, as well as the IVS aim at a new realization of the ICRS in the next years. It is planned to be completed concurrent with the 2009 IAU General Assembly.

The IAU as well as the IVS have working groups related to ICRF2. BKG and DGFI actively take part in the IVS Working Group for ICRF2, which was founded 2006 in Prague during the IAU General Assembly. The result of this working group will be submitted to the IAU Working Group. This IAU working group will then validate the ICRF2, and, in case of positive evaluation, be engaged in the formulation of resolutions to be adopted by the IAU. Both, DGFI and BKG submit catalogues, source position time series and other relevant results.

Effect of various analysis options on VLBI-determined CRF

In 2006, the effect of various analysis options on VLBI-determined CRF was investigated at DGFI (TESMER et al., 2006a, 2006b, and TESMER, 2007):

- different troposphere mapping functions and gradient models,
- choice of the data set (neglecting sessions before 1990 and 21 astrometric sessions),
- handling of sources that may not be assumed to have time-invariant positions,
- handling of the station network (estimate the station positions per session, as positions and velocities over 20 years, or fix them to a priori values).

The biggest, clearly systematic effects in the estimated source positions up to 0.5 mas were found to be due to different gradient models (esp. the selection of the a priori values and the constraints). The choice of the data set does generally not have a significant influence. This holds also (with several exceptions) for different options how to treat sources which are assumed to have time-invariant positions. Furthermore it turned out that fixing station positions to values not consistent to the solution itself can noticeably affect CRF solutions.

Interaction between CRF and TRF

At DGFI, a VLBI solution with a TRF, the EOP and a CRF being estimated simultaneously was established applying a non-biasing NNR and NNT datum for the TRF and NNR for the CRF (TESMER et al., 2004). Using such minimum datum conditions, biases were avoided which are due to fixed reference frames or other relevant parameters of the observation equations. HEINKELMANN et al. (2006) presents a similar solution and gives more technical details.

TESMER (2006) summarizes the results of a research project "consistent realization of reference systems by VLBI", supported by DFG (Deutsche Forschungsgemeinschaft, DR143-11). In this context, most interesting is: (1) The sparse southern VLBI observing network implicates a non sufficiently redundant observing geometry. This is why some parameters of southern sources and stations are significantly correlated in CRF and TRF solutions (like O'Higgins, Antarctica or Hobart, Australia). (2) This also holds for sources and stations, which were not observed in varying network constellations (like Crimea, Ukraine or Saint-Croix, Virgin Islands, USA).

Source position time series

Presently, if CRF solutions are computed with VLBI, one position is estimated for the whole data span (suitable data exists since 1984). This assumes the apparent position of the sources to be constant in time. But, there are some sources, for which today a constant model of the position

[1] Volker Tesmer: Deutsches Geodätisches Forschungsinstitut (DGFI), Alfons-Goppel-Straße 11, D - 80539 München, Germany, Tel. +49 - 89 - 2 3 0 31 11 98, Fax +49 - 89 - 2 3 0 31 12 40, e-mail tesmer@dgfi.badw.de

is not supposed to be suitable anymore. Engelhard and THORANDT (2006) computed time series of radio source positions and tested them for normal distribution to uncover such sources. TESMER (2006) also presents first source position time series.

GPS satellite orbits used as quasi celestial reference frame for satellites in Low Earth Orbit

ROTHACHER and SVEHLA (2003) sketch how Low Earth Orbiters (LEOs, such as CHAMP, JASON, GRACE etc), equipped with GPS receivers can be interconnected with global GPS solutions. Today, it is common habit to use the high flying GPS satellites as quasi celestial reference frame for the LEOs. As GPS observations from LEO receivers on-board are not subject to tropospheric delay, they can be used very well to estimate the position of the satellite in the orbit, e.g. with very high time resolution by means of kinematic approaches (SVEHLA and ROTHACHER, 2005). Details and more related publications are given in the reports "GNSS Positioning" and "Satellite Orbit Modelling" of Commission 4.

Satellite and receiver antenna phase center variations

In recent years, the effect of absolute instead of relative antenna phase patterns on geodetic GPS results was investigated in detail. Both, the receiver and the satellite antennas (which are part of the quasi celestial GPS reference frame) are subject to phase patterns. SCHMID and ROTHACHER (2003) estimated GPS satellite antenna phase center offsets and variations in nadir direction, azimuth-dependent phase center variations were demonstrated by SCHMID et al. (2005). STEIGENBERGER et al. (2007) compared different antenna phase center models, including the relative model used by the IGS so far, and the latest absolute IGS model igs05.atx (SCHMID et al., 2007): Terrestrial reference frames showed significant station displacements, e.g. horizontally by up to 5 mm and 1 cm in height. Details and more related publications are given in the report "Nuisance Effects in GNSS Positioning" of Commission 4.

LLR

MÜLLER et al. (2007) discuss the potential of Lunar Laser Ranging (LLR) to contribute to the realization of various reference systems, i.e. the terrestrial and selenocentric frame, but also the dynamic realization of the celestial reference system. Most of the benefit is due to the long-term stability of the lunar orbit, which is now observed by LLR for more than 36 years. They also discuss the option to deploy radio transponders to the moon, which would provide a strong tie to the kinematic VLBI system.

Gaia

Gaia is an (optical) astrometric satellite project of the European Space Agency (ESA), planned to be launched in 2011, as the successor mission to Hipparcos. It will measure 3-dimensional positions of about one billion stars, quasars and solar system objects as well as 3-dimensional velocities and physical properties of those objects (by multi-band photometry and spectrometry of each source). Being placed in an orbit around the Sun, at a distance of 1.5 million kilometres further off than Earth, it will be in a very stable thermal environment and a moderate radiation environment. Thus, measurements produced by Gaia will be of unprecedented accuracy of about several micro-arcseconds.

The Lohrmann Observatory at the Dresden Technical University coordinates a Gaia collaboration, REMAT (RElativistic Models And Tests). It is responsible for relativistic modelling of Gaia data and for the use of the microarcsecond astrometric observations to test of relativity and other aspects of fundamental physics. The Lohrmann Observatory also participates in all aspects of astrometric data processing for Gaia. Related publications are given in the references.

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Terrestrial Reference Frames (Global and Regional Frames)

D. ANGERMANN[1]

Introduction and overview

This report summarizes the major activities of the German geodetic institutions for the period from 2003 to 2007 in the field of global and regional terrestrial reference frames. It focusses on contributions for the IAG Sub-Commission 1.2 "Global Reference Frames" and the IAG Sub-Commission 1.3 "Regional Reference Frames". The Sub-Commission (SC) 1.3 consists of six sub-parts, which are the SC-1.3a "Reference Frame for Europe (EUREF)", SC-1.3b "Reference Frame for South and Central America (SIRGAS)", SC-1.3c "Reference Frame for North America (NREF)", SC-1.3d "Reference Frame for Africa (AFREF), SC-1.3e "Reference Frame for South East Asia and Pacific", and SC-13.f "Reference Frame for Antarctica (SCAR)". In the frame of the regional reference frame, the German institutions mainly contribute to Europe (EUREF), South and Central America (SIRGAS) and Antarctica (SCAR).

The contributions of German geodesists to the space geodetic observation networks are not addressed in this chapter. These activities are presented in the IUGG National Report of IAG Commission 4 "Positioning and Applications" in the sections 4.1 "Space Geodetic Techniques (VLBI, LLR, SLR, DORIS)" and 4.4 "Permanent GNSS Networks, including SAPOS". For a report on the German activities related to the combination and integration of space geodetic observations we refer also to the report of IAG Sub-Commission 1.1 "Combination of space geodetic techniques".

International Terrestrial Reference Frame (ITRF)

The International Earth Rotation and Reference Systems Service (IERS) is in charge of defining, realizing and promoting the International Terrestrial Reference System (ITRS). The realization of the ITRS, the ITRF, comprises a set of physical points on the Earth's surface with precisely determined positions and velocities in a specific coordinate system attached to the ITRS. The definition of the ITRS and the geophysical models to be used for its realization as the ITRF are specified in the IERS Conventions. Within the re-organized IERS structure (since 2001), the ITRS Product Centre hosted at the Institute Géographique National (IGN, France), is supplemented by ITRS Combination Centres, which have been established at "Deutsches Geodätisches Forschungsinstitut (DGFI)", IGN and National Resources Canada (NRCan). The ITRS Combination Centres are responsible for the computation of terrestrial reference frame realizations (ITRF) through the combination of data sets from space geodetic techniques, such as the Global Positioning System (GPS), Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS). A detailed description of the combination methodology of the ITRS Combination Centre at DGFI, which is based on the level of unconstrained normal equations, is provided in various publications (e.g. ANGERMANN et al., 2004 and 2006; MEISEL et al., 2005; DREWES et al., 2006).

The establishment of an ITRS Combination Centre at DGFI was partly funded by the "Sonderprogramm GEOTECHNOLOGIEN" of BMBF and DFG in the framework of the joint project "Integration der geodätischen Raumbeobachtungsverfahren und Aufbau eines Nutzerzentrums im Rahmen des internationalen Erdrotationsdienstes". This project includes the IERS Analysis Coordination (ROTHACHER et al., 2006), the IERS Central Bureau at "Bundesamt für Kartographie and Geodäsie (BKG)" RICHTER and SCHWEGMANN (2006); the joint IERS Combination Research Centre (CRC) of DGFI, the Research Facility for Space Geodesy (FESG) of the Technical University Munich and the Institute of Geodesy and Geoinformation (IGG) of the University of Bonn, as well as the CRC at GeoForschungsZentrum Potsdam (GFZ).

In its function as an ITRS Combination Centre, DGFI has computed a terrestrial reference frame realization 2003 based on multi-year VLBI, SLR, GPS and DORIS solutions with station positions and velocities. A comparison of the DGFI solution to ITRF2000 can be considered as a first "quasi-independent" quality control and external TRF accuracy evaluation. Detailed results of this comparison are provided in ANGERMANN et al. (2004).

In December 2004, the IERS released a call to the international geodetic services for providing time series of solutions (or normal equations) of station positions and Earth Orientation Parameter (EOP) for a new realization of the International Terrestrial Reference Frame 2005 (ITRF2005). The data should be epoch solutions (satellite observations weekly, VLBI session-wise) to allow detailed analyses, e.g. the detection of non-linear motions or discontinuities in the station coordinate series, and a rigorous combination. The International GNSS Service (IGS), the International Laser Ranging Service (ILRS), the International VLBI Service for Geodesy and Astrometry (IVS), and the International DORIS Service (IDS) provided the corresponding data sets.

[1] Detlef Angermann: Deutsches Geodätisches Forschungsinstitut (DGFI), Alfons-Goppel-Straße 11, D - 80539 München, Germany, Tel. +49 - 89 - 23 031 1117, Fax +49 - 89 - 23 031 1240, e-mail angermann@dgfi.badw.de

The contribution of the IVS for ITRF2005 has been computed by the IVS Analysis Coordinator's office at the Institute of Geodesy and Geoinformation of the University of Bonn (e.g. VENNEBUSCH et al., 2006). For this purpose the IVS Analysis Centers, two of them being the Leipzig Branch of BKG and DGFI, provided datum-free normal equation matrices in Solution INdependent EXchange (SINEX) format for each 24-hour observing session to be combined on a session-by-session basis. The German contributions to the ILRS include the computation of SLR time series solutions by the ILRS Analysis Centres at DGFI and GFZ and their combination performed by the ILRS Backup Combination Centre at DGFI (e.g. KELM, 2003, MÜLLER et al., 2005). The German contributions to the IGS include the processing of GPS time series solutions by the IGS Analysis Centres at GFZ and ESOC, Darmstadt.

Besides the official IGS solutions submitted for the ITRF2005 computation, a complete reprocessing from the raw GPS observations has been started by the FESG of the Technical University Munich and the Institute for Planetary Geodesy (IPG) of the Technical University Dresden (e.g. STEIGENBERGER et al., 2006). In 2006, also the IGS has decided to perform such a homogenous reprocessing and recombination of the GPS data, which then will serve as input for future ITRF realizations.

DGFI and IGN computed each one solution for ITRF2005 using the times series solutions (or normal equations). The common processing of time-dependent station positions and EOP shall ensure the consistency of the terrestrial reference frame and the orientation of the Earth in space. Both ITRS Combination Centres used their own software and applied their preferred methodology. A description of the combination methodology applied at DGFI is published in ANGERMANN et al. (2007). Comparisons between the IGN and DGFI solutions show a good agreement after similarity transformations, but a significant difference in the SLR scale was found due to the different computation strategy. It has been agreed by IGN and DGFI to perform further test computations to assess the effect of the differences in the combination strategies.

Various studies related to the terrestrial reference computations were performed, which include the weighting of the different space geodetic observations (e.g. KELM, 2003), the local tie implementation within the inter-technique combination (e.g. KRÜGEL and ANGERMANN, 2007) and the effect of time-variable effects in station positions on the terrestrial reference frame results (e.g. MEISEL et al., 2007). FESG and GFZ Potsdam performed investigations on the impact of the combination of GPS and Galileo as well as of GPS and Low Earth Orbiters (LEO) on the global reference frame (e.g. ROTHACHER and SVEHLA, 2003; KÖNIG et al., 2005; ZHU et al., 2003). In a cooperation between the Geodetic Institute of the University Hannover and DGFI a new stochastic approach was developed for the intra-technique combination, assuming that the variance of the input data sets of different Analysis Centres have a common part resulting from the variance of the observations (observation noise) and an individual part coming from the individual analysis strategy (analysis noise). First results of this new stochastic approach are presented in KUTTERER et al. (2007).

Reference Frame for Europe (EUREF)

The EUREF Sub-Commission was constituted at the IUGG General Assembly held in Vancouver, 1987, under the umbrella of Commission X – Global and Regional Geodetic Networks of Section 1 – Positioning. As a result of the new IAG structure at the IUGG General Assembly held in Sapporo, 2003, EUREF was integrated within Sub-Commission 1.3 "Regional Reference Frames" (e.g. TORRES et al., 2005).

The objective of EUREF is the definition, realization and maintenance of the European Reference Systems, in close cooperation with the IAG components and EuroGeographics, the consortium of the National Mapping and Cadastre Agencies (NMCA) in Europe. The Terms of Reference (ToR), which were adopted at the annual symposium held in Bratislava (June 2004), contain the description of EUREF, its objectives, activities, organisation and the rules for membership according to the general rules expressed in the Statutes and By-laws of IUGG and IAG (see *http://www.euref-iag.net/html/ Overview_of_EUREF_ Terms_of_reference.html*).

The forum, where activities are discussed and decisions are taken is the annual symposium, organized since the EUREF foundation in 1987. Current activites are governed by the Technical Working Group (TWG). The results of EUREF are available in the symposia proceedings as well as on the EUREF homepage (*http://www.euref_iag.org/*).

Since the beginning, Germany is intensively engaged in EUREF. The secretariat of EUREF is incorporated at the German Geodetic Commission in Munich. Several German geodesists are members of the TWG. The organization of numerous EUREF campaigns was organized and mostly subsidized by BKG in Frankfurt a.M. and Leipzig. Numerous colleagues from other countries were guests of BKG to be trained in the analysis of GPS networks. The proceedings of the EUREF symposia were compiled by the EUREF President and Secretary, the printing was financed by BKG.

German institutions also contribute significantly to the EUREF Permanent Network (EPN). The EPN is a network of continuously operating GNSS stations, primarily installed for reference frame maintenance. Since 2003, more than 30 new EPN stations were installed, bringing the total number of stations to almost 200, from which 16 stations are operated by German institutions. The current status of the EPN is visible at the EPN Central Bureau web site at *http://www.epncb.oma.be*. In order to optimise the data processing within the EPN, the principle of distributed processing is used. In this approach the EUREF Permanent Network is divided in sub-networks, which are separately processed by different EPN Local Analysis Centres (LAC's). They submit weekly free-network solutions (SINEX format) to the EPN Regional Data Centre at BKG. There are two LAC's operated by German institutions: The Bavarian Committee for International Geodesy in Munich (BEK: "Bayerische Kommission für die Internationale

Erdmessung") and BKG. The EPN Combination Centre presently hosted at BKG is responsible for combining the EPN sub-network solutions into one European solution submitted to IGS. The EUREF combined solutions are computed by the EPN Analysis Coordinator (e.g. HABRICH 2003, 2004, and 2005). The resulting free-network solutions (official EUREF combined solution) are made available as SINEX files to the IGS Global Network Associate Analysis Centres (GNAAC). The data centre of BKG is providing access to observation and analysis results of the EPN through its server.

BKG is leading the EUREF activities concerning the vertical networks (UELN – Unified European Levelling Network / EVS – European Vertical System) and its integration in the European Vertical GPS Reference Network (EUVN) as well as the European Combined Geodetic Network (ECGN). The UELN was extended by the first order levelling network. In May 2004 the Danish network block was substituted by a new version of the same epoch and in December 2004, the 5th Primary Levelling of the Netherlands was handed over. These two data sets were included in the UELN data base at BKG. The data of the most recent levelling networks of Finland, Norway and Sweden are expected in the near future (SACHER et al., 2007). The European Combined Geodetic Network (ECGN) is a kinematic network for the integration of time series of spatial/geometric observations (GNSS – GPS/GLONASS and in the future Galileo), gravity field related observations and parameters (precise levelling, tide gauge records, gravity observations, Earth and ocean tides), and supplementary information (meteorological parameters, surrounding information of the stations, e.g. eccentricities and ground water level). BKG contributes to the development of the ECGN and participated in the preparation of the "Call for Participation" for the ECGN project. The first call for participation in the project was directed to the implementation of the ECGN stations. These stations include the observation techniques GNSS, gravity (super conducting gravimeter and/or absolute gravimeter), levelling connections to nodal points of the UELN and meteorological parameters. As a result of this first call a total of 50 ECGN stations (8 core stations, 42 stations with the "ok-status") were selected. From the 74 originally proposed stations 7 were identified as candidates and 17 as proposed stations (IHDE et al., 2005). More information of the current status and the distribution of ECGN stations is availabe at the homepage of the ECGN project hosted at BKG (*http://www.bkg.bund.de/ecgn*). After the consolidation of the ECGN network configuration and the integration of the stations in the EPN network, the absolute gravimeter infrastructure has to be developed and a data base for absolute gravity measurements has to be realized (IHDE et al., 2007).

Other EUREF related activities with the contribution of German geodesists are the EPN Special Project "Troposphere Parameter Estimation" (SÖHNE and WEBER, 2004) as well as investigations and developments with the "EUREF – IP Pilot Project" (WEBER and GONZALES-MARTESANZ, 2005). EUREF-IP Ntrip Broadcaster Implementation is available now in BKG, FGI, FÖMI, GURS, IGNE, Swisstopo. As a practical application a successful EUREF-IP Ntrip Driving Test has been performed in Finland over a distance of 18 km.

The Institute of Physical Geodesy of Technical University Darmstadt is member of the Central European GPS Geodynamic Reference Network (CEGRN) Consortium. The institute took part in the CERGN epoch campaign in 2005 and in the evaluation of this campaign. Furthermore the combination solutions of all available campaigns were combined to an integrated estimation of station coordinates and velocities (e.g. CAPORALI et al., 2006, DRESCHER et al., 2006, HEFTY et al., 2006).

Reference Frame for South and Central America (SIRGAS)

Sub-Commission 1.3b encompasses the activities developed by the "Geocentric Reference System for the Americas" project (SIRGAS). The long-term objective is the definition and realization of a unified reference frame for South and Central America, consistent with the ITRF, besides promoting the definition and the establishment of a unique vertical reference system (e.g. FORTES et al., 2005, FORTES et al., 2006).

Three Working Groups (WG) were established within SIRGAS: WG1: Reference Frames, WG2: Geocentric Datum, WG3: Vertical Datum. Several scientists from Germany are members of the Working Groups and LAURA SÁNCHEZ (DGFI) was confirmed as the president of the Working Group 3.

DGFI contributes to the SIRGAS Working Group 1 as an IGS Regional Network Associate Analysis Centre for SIRGAS (IGS RNAAC SIR) since 1996 (e.g. SEEMÜLLER et al., 2005). Weekly coordinate solutions including all available observations of this network are generated and delivered to the IGS Global Data Centres. Since 2003 a number of new stations have joint the SIRGAS network, bringing the total number to more than 120 stations. The number of participating stations will increase dramatically, especially in Argentina, Brazil and Columbia.

The IGS RNAAC SIR processing is currently done with the Bernese Processing Engine, version 5.0. DGFI is providing weekly position solutions as support to all South and Central American countries. A new accumulated solution DGF06P01 was computed including data from June 30, 1996 to June 17, 2006. It provides positions of 85 stations and velocities of 71 stations which have contributed to at least 52 weekly solutions.

Results of the SIRGAS campaign 2000 and American geocentric reference frame were released in 2003. The processing of the 2000 observation data was performed by three analysis centres at DGFI and BEK in Munich as well as IBGE in Rio de Janeiro, Brazil (DREWES et al., 2005). Using the velocities of the SIRGAS stations together with the results of the IGS RNAAC SIR processing, DGFI and the Geophysical Institute of the University Karlsruhe have estimated the deformation of the South American crust from finite element and collocation methods (DREWES and HEIDBACH, 2005). These deformation model provides the basis to derive the velocity field for South America.

At the workshop of the SIRGAS Working Group 1 in Rio de Janeiro, August 16-18, 2006, it was decided to install Experimental Analysis Centers (EAC) for SIRGAS under the responsibility of Latin American institutions. The test phase of the one-year experiment has started in October, 2006 in order to prove the operational capacity of the EAC's to provide weekly coordinate solutions and to support the IGS RNAAC SIR processing.

Reference Frame for Antarctica (SCAR)

The objective of IAG Sub-Commission 1.3f is the definition, realization and maintenance of the reference frame for Antarctica (DIETRICH 2005).

The SCAR GPS Campaigns 2004 and 2005 were carried out in the Australian summers 2004 and 2005. All together, the data of 36 sites are now collected in the SCAR GPS database with the year 1995. The new as well the existing data were reanalysed with the Bernese Software, Version 5.0. First results were presented at the XXVIII. SCAR Metting in Bremen (Germany) in July 2004.

For the ITRF2005 a densification solution for Antarctica was computed and submitted to the IERS Central Bureau at February 28th, 2005. The solution contains 31 IGS sites and 27 SCAR Campaign sites.

During the XXVIII. SCAR meeting in Bremen the members of the IAG Sub-Commission 1.3f met and discussed the working plan of the SCAR Group of Experts on Geodetic Infrastructure in Antarctica (GIANT) and fixed it for the years 2004 until 2006. R. DIETRICH (TU Dresden) was selected as new chairman of GIANT. The members of GIANT represent the SC-1.3f.

The International Polar Year 2007/2008 will be an intensive period of scientific activities in the polar regions. It is organized jointly by ICSU and WMO, and a broad range of coordinated, international projects are in preparation. The SC-1.3f will actively participate in the frame of the project POLENET (Pole Earth Observing Network).

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Vertical Reference Frames

J. IHDE[1]

Introduction

The contributions of German scientists were focussed to the development of concepts for the definition and realization of vertical reference systems as well as to implementation activities in the global, European and national frame. The work was organized in interdisciplinary working groups, mainly the Inter-commission Project 1.2 Vertical Reference Frames, a common Project of Commission 1 and Commission 2, the Sub-commission for Reference Frames in Europe EUREF, and the Working Committee of the Surveying Authorities of the German States (AdV).

The combination of different geodetic techniques is an integrated part of all concepts for height determination and the realization of vertical reference frames. Especially the satellite gravity missions CHAMP, GRACE and in the next step GOCE in connection with local geoid densifications and GNSS measurements will lead to an essential progress for the unification of the different height reference frames.

Global Vertical Reference System (GVRS)

In 2003 IAG has founded the Inter-commission Project 1.2 Vertical Reference Frames to study the consistent modelling of both, geometric and gravimetric parameters and to provide the fundamentals for the installation of a unified global vertical reference frame.

The main tasks were:

- Elaboration of a proposal for the definition and realization of a global vertical reference system;
- Study of combination procedures for height data sets from different techniques;
- Study of information on regional vertical systems and their relations to a global vertical reference system for practical applications;
- Unification of regional (continental) height systems;
- Harmonization of globally used height data sets.

The results of the work of the ICP1.2 are documented in Conventions for the Definition and Realization of a Conventional Vertical Reference System (CVRS, CVRF).

In the CVRS/CVRF conventions a general concept for the definition and realization of a unique, global vertical reference system is worked out. The CVRS conventions are aligned to the IERS 2003 Conventions. Parts of the IERS 2003 conventions are the basis for the CVRS conventions.

A global unified vertical reference system as International Vertical Reference System (IVRS) can be realized by:

- A global network of stations coordinated in ITRF with co-location between permanent GNSS, tide gauges, in some stations gravity permanent (SG) and periodically (AG)
- A conventional global gravity model (CGGM) from satellite gravity missions only
- Both based on a set of conventionally numerical standards.

Regional and national height reference systems can be integrated in an IVRS by GNSS/levelling aligned to ITRF and using the CGGM and the numerical standards.

Proposed items for continuation:

- Discussion of the results of ICP1.2 (GGAS action)
- Initiation of a pilot project for an IVRS realization on the basis of the TIGA-PP, GGP and IGFS for AG and a CGGM (call for participation as IGFS action)
- Decision about numerical standards as task of GGOS in cooperation with IAU.

The project continuation shall realize in cooperation with other organizations, especially the International Association of Hydrological Sciences (IAHS), the International Association for the Physical Sciences of the Oceans (IAPSO), the International Hydrographic Organisation (IHO), the International Federation of Surveyors (FIG), and the Interservice Geospatial Working Group (IGeoWG) of NATO.

German scientists basically contributed to this working group by:

- Definition and realization of a global vertical datum: the zero height level. Since the different physical height types (orthometric and normal heights) refer to different reference surfaces (namely, geoid and quasigeoid), the studies are focused in appointing a unified reference surface, which serves as a zero level to both types of heights and allows the different countries to keep the physical heights they prefer, but in a unified vertical reference system.
- Determination of a conventional geopotential value (W0). Although the W0 value of a vertical datum can arbitrarily be selected, it is preferred to introduce a quantity, which agrees with the state of the art of the present observing techniques of the Earth's gravity field. In this way, W0 was determined by applying different approaches (mean value of the geopotential values at the sea surface, solution of the fixed gravimetric geodetic

[1] Johannes Ihde: Bundesamt für Kartographie und Geodäsie, Richard-Strauss-Allee 11, D-60598 Frankfurt am Main, Germany, Tel. +49 - 69 - 6333 206, Fax +49 - 69 - 6333 425, e-mail johannes.ihde@bkg.bund.de

boundary value problem, etc.), different mean sea surface models (CLS01, KMS04, GFSC00.1, and a series of annual models from 1993 to 2001 derived at DGFI from T/P), and different global gravity models (EGM96, TEG4, GGM02S, EIGEN-CG03C, EIGEN-GL04S).

– Unification of the existing vertical datums. This topic is concentrated on the formulation of a combined system of observation equations based on spirit levelling, GNSS positioning, and geoid determination. It includes the common analysis of tide gauge registrations, satellite altimetry data analysis and GNSS positioning at those tide gauges which serve as vertical datums in the classical height systems. This analysis is carried out in the frame of the IGS TIGA project.

A meeting of the Working Group "Theoretical Geodesy" took place to the topic "Fundamental questions of vertical datum and a world height system" in the Institute of Theoretical Geodesy of the University of Bonn on September 12th, 2006. Science colleagues from Germany and the Netherlands as well as representatives of the national survey from a few federal states took part in the meeting. In the course of the informal meeting a number of lectures was given followed by dedicated discussions. It turned out that the issue of the choice of a suitable vertical datum and of the connection of regional datum systems, but also the question of a practicable solution that is closely connected to this arouse intense discussions again and again.

European Vertical Reference System (EVRS)

The main activities to realize the European Vertical Reference System (EVRS) are carried out in the frame of the IAG Sub-commission EUREF. In the last four years EUREF initiated several height projects: The European Combined Geodetic Network (ECGN), the densification of European Vertical Reference Network (EUVN-DA) and the readjustment of the United European Levelling Network (UELN). The combination of the UELN and ECGN activities will lead to an EVRS 2007 solution.

The Federal Office for Cartography and Geodesy (BKG) is the responsible EVRS data and analysis centre. All European levelling data of EUREF are stored and analysed at BKG including the information systems to present the results via internet.

The European activities were related in two directions:

i. Selection and validation of related height information
ii. Preparation of a new EVRS solution to store all height related geo-information data of the European Commission in a homogeneous vertical system.

The updating and maintenance of the UELN databank was continued by the data of the national Bulgarian First Order Levelling Network, the data of the current Danish First Order Levelling Network, the data of the 5th precision levelling of the Netherlands, the data of the newly measured 1st order levelling networks of Finland, Norway and Sweden. In this context the 'Land Uplift Model', used by NGK for the readjustment of Scandinavia, was transferred. The measuring data by means of this model were reduced to the epoch 2000.

Germany participated in the activities carried out for the EUVN_DA project within the scope of the provision of the levelling heights of the stations in the EVRF2000 system. The project serves to derive a new European geoid. To be able to ensure that in the case of an interim change of the net datum and the integration of new data into the UELN, respectively, the heights of all EUVN_DA stations do refer uniformly to the relevant current epoch, the geopotential differences between the EUVN_DA stations and the neighbouring UELN nodal points were adopted into the database, thus they will enter into any future UELN adjustment.

Re-measurement of the German First Order Levelling Network (DHHN)

Since 2003 the conceptual preparation of a re-measurement of the German First Order Levelling Network (DHHN) was performed in the frame of the Working Group "Renewal of the DHHN92" of the AdV. On the basis of an analysis of the current state of height networks in Germany the Working Group discussed urgent questions of effort for and accomplishment of a renewal of the levelling network. Objectives of a re-measurement of the levelling network are the examination of the official height system DHHN92 for detection of stresses and height changes (diagnosis), the optional introduction of a new official height status, the integration of the height reference system into a future integrated spatial reference system and the creation of bases for scientific investigations (e.g. determination of recent crustal movements).

Correspondingly, the concept comprises besides digital geometrical precision levelling from the state surveying agencies during the years 2006 – 2011 an additionally epoch equal GNSS campaign integrating 250 selected points of the levelling network and nearly 300 reference stations of different GNSS networks (IGS, EPN, GREF, SAPOS) in 2008. In addition, BKG will carry out absolute gravity measurements on 100 of the field stations as from 2008.

As economically reasonable variant that is realizable within a period of about 5 years, at first a partial renewal of the existing network with a levelling length of about 14.000 km (about 50 % of the existing network) was intended. By now, additional efforts of the surveying agencies let expect re-levelling of approximately 75% of the first order network. The network configuration follows the run of existing 1st order levelling lines. For linking the network to the neighbouring states and the connection of coast gauges, attention was paid to the inclusion of levelling lines along the state boundaries and the coasts of North and Baltic Sea. In addition, the selected lines should have as little height difference changes as possible between the previous two levelling epochs. To check the compliance with these conditions the horizontal gradients of vertical height difference changes were determined and analysed from the observations of the last two levelling epochs that are stored in the DHHN databank.

The draft network of the levelling to be measured was revised in accordance with the comments and proposals of the Land survey authorities, whereby the border crossing-points with the neighbouring countries have been integrated into the draft network for the purpose of linking the DHHN in future with the European Levelling Network UELN. The sub-surface control point groups Wallenhorst, Flechtingen and Hoppegarten were discussed as potential datum points within the frame of a constraint-free adjustment of the levelling network.

There exists a close cooperation between the two DHHN computing centres of the State Survey Administration of Nordrhein-Westfalen (NRW) and of BKG. The NRW computing centre provides the software for the pre-valuation of the levelling data in the field. First arrangements have been made concerning the delivery of the pre-valuated data. A test network was evaluated by both computing centres with identical results for the purpose of comparing the evaluation programs and evaluation technologies employed.

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Satellite Altimetry

W. BOSCH[1]

Satellite altimetry provides a precise mapping of the ocean surface and monitors its temporal variations. Thereby this space technique contributes essentially to the solution of fundamental problems of physical geodesy: the mean sea level does not only realize two third of the Earth figure, it also approximates very closely the geoid, the equi-potential surface of the Earth gravity field serving as a global height reference. Sea level variations allow estimating ocean mass redistribution, one component of the global hydrological cycle currently observed by the GRACE gravity field mission. Synergies between satellite altimetry and the upcoming high resolution gravity field mission GOCE will allow obtaining a detailed view of the sea surface topography, the separation of sea level and geoid. This is equivalent to the knowledge of the ocean surface currents which in turn can be used together with vertical density profiles to get a reliable estimate of heat flux and deep ocean currents. All together these relationships demonstrate that satellite altimetry will contribute to an improved understanding of dynamic processes in the system Earth and will have to be an essential component of Global Earth Observing Systems (GEOS).

Applications in General

There are only a few publications by BOSCH (2002, 2004a) focussing on specific geodetic applications of satellite altimetry. A summary report on global sea level change, altimetry, GNSS and tide gauge measurement treated on session GP2 of the joint Assembly of IAG, IAPSO, and IAB is given by BOSCH (2005a). Of general interest is also the mid-term report of the IAG Inter-Commission Project 1.1 on Satellite Altimetry (BOSCH, 2005b) indicating the efforts to investigate feasibility and scope of an International Altimeter Service (IAS). Synergies between the new gravity field missions CHAMP, GRACE and GOCE and altimeter satellites are identified in ILK et al. (2004), a document describing the foundations of a new DFG priority program for mass transport and mass distribution in the system Earth.

Calibration and Validation

Although satellite altimetry may be already considered as operational space technique there are continuous requests for calibration and validation of the altimeter systems. SCHÜLER (2004) and SCHÜLER and HEIN (2004) contributed to the ESA project for the range calibration of the ENVISAT radar altimeter by deploying GPS equipped Sea Buoys. Such buoys allow a kinematical determination of the sea level and a comparison with contemporary altimeter observations. FENOGLIO-MARC (2003) focused on cross-calibration of the ENVISAT altimeter range in the Mediterranean Sea using multi-satellite altimetry and tide gauge data. BOSCH (2004b) described a global procedure for a simultaneous crossover adjustment of contemporary altimeter missions. The foundation of this novel approach, a discrete crossover analysis, is documented in BOSCH (2007). An extended multi-mission cross calibration with upgraded data from up to five simultaneously operating altimeter systems has been performed by BOSCH and SAVCENKO (2007). A basic prerequisite for any altimeter range calibration are precise satellite ephemeris. RUDENKO et al. (2006) used one of the most recent GRACE-based gravity field models to generate precise orbits for ERS-1, ERS-2 and the TOPEX/Poseidon altimeter satellites.

Sea Level Variability

German scientists participated in several studies of sea level variability for the North Atlantic, the Mediterranean Sea and other European Seas. Very few investigations focus on global sea level change. ESSELBORN (2003) studied the sea level variability in the German Bight using satellite altimetry data during the 1990's. The long-term variability in the European Seas observed from ERS-2 and TOPEX altimetry and tide gauge stations has been investigated by FENOGLIO-MARC and GROTEN (2004). Dual-crossovers differences in the period 1995-2001 show a time-dependence of the relative range bias with a negative trend of a few mm/yr. FENOGLIO et al. (2005) also studied the contribution of wind and pressure and steric effect in the Mediterranean Sea and the agreement between sea level observations from altimetry and tide gauge stations in Southern Europe. Studies on the global sea level variability in the last decade were performed by FENOGLIO and BECKER (2006). Within the EU project ESEAS (European Sea Observation Service) TSIMPLIS et al. (2005) investigated the sea level change both at global and regional scales using altimetry and tide gauge data. KUHN et al. (2005) studied the low frequency variation of the North Atlantic sea level by means of principal component analysis and found clear indication of a weakening or displacement of the Gulf Stream. In the Baltic Sea the variability of altimetry derived sea surface heights has been compared with numerical models, see NOVOTNY et al. (2006).

[1] Wolfgang Bosch: Deutsches Geodätisches Forschungsinstitut (DGFI), Alfons-Goppel-Straße 11, D-80539 München, Germany, Tel. +49 - 89 - 23 031 1115, Fax +49 - 89 - 23 031 1240, e-mail bosch@dgfi.badw.de

Mean Dynamic Topography, Geoid, and Gravity Field

The deviation between mean sea level and the geoid, known as mean dynamic topography (MDT), is of interest for both, geodesy and oceanography. The knowledge of the MDT may help to derive local improvements of the marine geoid from satellite altimetry data as performed, for example, in the western Mediterranean Sea by FENOGLIO-MARC and GROTEN, (2003). In the Baltic Sea NOVOTNY at al. (2005) investigate the combination of sea level observations and an oceanographic model for geodetic applications. LOSCH et al. (2002) and LOSCH and SCHRÖTER (2004) take the opposite perspective, consider altimetry and geoid as input for Box inverse models, study the omission error of the geoid and identify the limitations imposed by available geoid models for estimating ocean circulation from hydrography and satellite altimetry. The scientific report of DOBSLAW et al. (2004) describes how the geostrophic surface velocity field can be derived from TOPEX altimetry and gravity field models of CHAMP and GRACE. The impact of CHAMP derived geoid on the calculation of the mean sea surface by combining oceanography, altimetry, and gravity data is outlined in SEUFER et al. (2005). FLECHTNER at al. (2006) demonstrate that there is a mutual benefit by improving the orbit determination of altimeter satellite by means of GRACE based gravity field models and including satellite altimetry data into high resolving gravity field models. KIVMAN et al. (2005) present first results of assimilating the absolute dynamic topography into a steady state finite element ocean model. SIDORENKO et al. (2006) consider the inverse estimate of the North Atlantic circulation and discuss the influence of the fine resolution dynamic topography derived within the international GOCINA project. Within the new DFG project STREMP FENOGLIO-MARC et al. (2006, 2007) investigate mass variation and mean dynamic topography in the Mediterranean Sea and Black Sea regions. The publications of FREEDEN et al. (2004, 2005) develop the theoretical background and aspects of scientific computing for a multi-scale approximation of the geostrophic velocity field and suggest a multi-scale modeling of the ocean circulation. FENGLER and FREEDEN (2006) describe the application of vector and tensor spherical harmonics for the solution of the Navier-Stokes differential equation on the sphere. FEHLINGER at al. (2007) use locally supported vector wavelets to achieve an approximation of the sea surface topography from the geostrophic flow field. Satellite altimetry is also capable to assess the quality of those gravity field models which have been used to generate the precise orbits of the altimeter satellites. This is possible because gravity field induced orbit errors map into long-term means of crossover differences, the discrepancies of sea surface heights. FÖRSTE et al. (2003) perform a tentative calibration of the EIGEN-2 gravity field. In subsequent investigations KLOKOCNIK et al. (2003, 2005) assess the spectral accuracy of EIGEN-1S and -2 gravity fields and justify degree dependent scaling factors for their covariance matrix. A new GRACE based gravity field model has been used by BOSCH (2005c) to investigate defectiveness of the marine gravity data, derived by processing satellite altimeter data.

Coastal Application, Tides, and Tide Gauges

Satellite Altimetry has important application in coastal zones: The evolution of the mean sea level is of great impact for the protection of the coastal ecosystem. Sufficient long altimeter time series allow estimating all major ocean tide constituents and the coastal mean sea level can help unifying height systems. Unfortunately, altimeter observation approaching the coast are degraded – the radar echo is already affected by land surface, the ocean tide corrections become erroneous, and the onboard radiometer fails due to non-ocean reflectivity. Tide gauge observations are complementary to satellite altimetry. The high precision, quasi continuous records are in general available for much longer time periods as altimetry. If tide gauges are controlled by continuously observing GNSS systems, the sea level trends can be corrected for vertical tectonic motions and can be used to control the long term stability of altimetry. Thus, comparing time series of altimetric sea surface heights and tide gauge records are of great interest. An attempt to perform an absolute comparison for tide gauges at the coast of Venezuela is published by ACUÑA and BOSCH (2004). The closure between the trends of sea level, tide gauge and tectonic motion can be also used in an inverse sense: FENOGLIO-MARC et al. (2004) estimated vertical land motion in the Mediterranean from altimetry and tide gauge stations. This work was part of the COSSTAGT project, a German contribution to the Ocean Surface Topography (OST) Science Plan for Jason-1. Intermediate results of the COSSTAGT project, combining altimetry, tide gauge records, terrestrial gravity as well as new satellite-only gravity field models for estimating the sea surface topography in coastal areas are described in BOSCH et al. (2007). FORBERG et al. (2004) report about several bottom mounted tide gauges in the North Sea which can be used to monitor altimetry measurements form ENVISAT, TOPEX, Jason1 and GFO. ESSELBORN (2003b) investigated the impact of mean sea level rise on the tidal water elevation. SAVCENKO and BOSCH (2004) performed a tide analysis in the Patagonian shelf by using the complementary tracks of Jason-1 and TOPEX during its extended mission with a shifted ground track. The approach is further extended to a multi-mission tide analysis (SAVCENKO and BOSCH, 2007), demonstrating for the North-West European shelf that sufficient long altimeter time series allow to estimate and de-correlate all major tidal constituents. RICHTER et al. (2005) compared and combined coastal off-shore tide gauge measurements from Eivissa Island in the Western Mediterranean Sea. MARCOS et al. (2007) focussed on estimates of the decadal sea level trends in the Bay of Biscay, derived from tide gauges, GPS, and TOPEX altimetry data.

Specific Applications

A few additional investigations not classified into the previous sections documented important research on new altimeter technologies or specific application of satellite altimetry. KELLER et al. (2004) investigated a new concept of non-nadir altimetry using GPS signals reflected at the sea surface. HOWARD et al. (2006) reported results of a project on the Antarctic Ice Shelf in Dronning Maud Land analyzing ice thickness, altimetry derived ice surface heights and ice flow observations. Over ice shields the analysis of radar altimetry data requires correction accounting for the slope of the ice surface. This has been applied to the region of the subglacial Lake Wostok/Antarctica, see ROEMER et al. (2007). Dual frequency altimeters allow an in-situ estimate of the Total Eelectron Content (TEC). BRUNINI et al. (2005) compared TOPEX and GPS derived TEC values and investigated the temporal and spatial variability of their differences.

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COMMISSION 2

GRAVITY FIELD

Overview and Highlights

N. Sneeuw[1]

Introduction

The US-German mission GRACE (Gravity Recovery and Climate Experiment) has celebrated its fifth birthday in March 2007. In July 2007 the German mission CHAMP (Challenging Mini-Satellite Payload for Geophysical Research and Application) will be in orbit for exactly 7 years. These missions have dominated the gravity field mapping scene during the past four years. They have led to static and time-variable gravity field models with far reaching impacts in neighbouring geoscience disciplines. They have also spurned a host of new methodologies for gravity field modelling and recovery techniques, most notably those techniques that consider the observations as *in situ* gravity field functionals. At the same time the preparations for a December 2007 launch of the European mission GOCE (Gravity field and Ocean Circulation Explorer) are ongoing. The German contributions over the past four years to these and other developments will be highlighted in the following.

From an international viewpoint the German geodetic community is well positioned. It borrows much of its strength from long-term involvement in the area of satellite gravimetry. Moreover, more recently, two large research programs came into being. The German Ministry for Education and Research (BMBF) supports a so-called Geotechnology Program with the title *Observation of System Earth from Space*, whereas the German Research Foundation (DFG) supports a priority program SPP1257 titled *Mass transport and mass distribution in the system Earth*, both of which are devoted (to a large extent) to space gravimetry.

Gravity field satellite missions

CHAMP has been in orbit for exactly 7 years now. The orbital decay due to solar activity predicts a remaining life time at least up to end of 2008. GRACE has been in orbit for five years now. The predicted lifetime calculated from gas consumption, thruster activations and solar activity is at least 2011. Despite a setback during system testing, GOCE is now ready for launch in December 2007.

The gravity field models resulting from these missions are described in the section on Global Gravity Field Modeling. The series of EIGEN models from the GeoForschungs-Zentrum, Potsdam, consisting of both satellite-only and combination models, has become a standard. The European data center for CHAMP and GRACE products (ISDC) is housed at GFZ Potsdam. At the same time, a number of "competing" gravity models have been developed by university groups (Bonn, Munich, Kaiserslautern), mostly based on alternative modelling schemes.

Pre-mission GOCE activities were focused on sensor analysis, calibration/validation schemes and, for a large part, preparation for the actual GOCE data analysis. The latter is done in the framework of the ESA (European Space Agency) funded project High-level Processing Facility (HPF) whose PI is IAPG, TU Munich, but with strong cooperation from several other German groups. First results are to be expected roughly one year after launch.

Through the gravity field satellite missions the goal of "10^{-9} geodesy", which was previously attained by geometric geodesy, has now been achieved by physical geodesy too, at least at the larger length scales. GOCE will further enhance the spectral bandwidth for which "10^{-9} physical geodesy" is valid.

Methodological advances

In the pre-CHAMP era conventional gravity field modelling from satellite observables was rooted in dynamic satellite geodesy and orbit perturbation theory. It involved large-scale computations, extensive software packages and, at an institutional level, a certain critical mass. As a result only a few global players were involved in global gravity field modelling. This approach is still pursued, e.g. in the EIGEN series of gravity models from GFZ. The observables from CHAMP, GRACE and GOCE, on the other hand, can be modelled as *in situ* observables in the theoretical framework of classical physical geodesy. This enabled smaller, mostly university based groups to get involved in global (but also regional) gravity field modelling from satellite-borne gravimetry, and to produce competitive gravity models, see above. The methodological advances are more extensively described in the section Gravity Field Theory.

Geoscience Applications

GRACE is geodesy's window into neighbouring geoscience disciplines. The monthly gravity field solutions represent global mass redistribution between cryosphere, hydrosphere, atmosphere and oceans. This fact was the main driver behind the aforementioned DFG-program on *Mass transport and mass distribution in the system Earth*. Some projects in this program deal with oceanographic modelling for and from GRACE. In other projects the continental hydrological cycle is constrained through GRACE. The topic of yet other projects is the monitoring of the Earth's

[1] Nico Sneeuw: Geodätisches Institut, Universität Stuttgart, Geschwister-Scholl-Str. 24D, D-70174 Stuttgart, Germany, Fax +49 - 711 - 685-83285, Tel. +49 - 711 - 685-83390, e-mail sneeuw@gis.uni-stuttgart.de

response to past and present ice mass loss by a combination of GRACE and terrestrial data, e.g. absolute gravimetry in Fennoscandia.

As indicated in the section on Temporal Gravity Field Variations, before GRACE the determination of the global time-variable gravity field was based on SLR. Only the very lowest spherical harmonic degrees could be resolved. GRACE has changed that situation dramatically: it provides (sub-)monthly gravity field solutions down to scales of, say, 500 km. The mission thus enables, amongst others, the monitoring of hydrological budgets at river-basin scale.

To achieve highest spatial and temporal resolution much effort has been put into addressing the typical problems with GRACE, namely its characteristic error behaviour with North-South correlated stripes. As an example, the OMCT (Ocean Model for Circulation and Tides) of TU Dresden is a standard tool for preventing sub-monthly ocean mass signals to alias into the monthly solutions, both for US and European data processing centres.

Regional gravity field and geoid modelling

With the German Combined Quasigeoid GCG05, a joint product between IfE, Hannover, and BGK, Frankfurt, Germany has a new height reference surface, which serves as a standard for converting between GPS ellipsoidal heights and normal heights. The IfE is also PI of IAG Commission 2 project CP2.1, EGGP (European Gravity and Geoid Project), that will provide regional geoid and quasigeoid models within Europe. As documented in the section on Regional Gravity Field Modelling, the EGGP will provide accuracies of 3–5 cm at continental scales and 1–2 cm over shorter distances up to a few 100 km. This clearly outperforms the previous *de facto* standard of EGG97.

Another Commission 2 project CP(2.4), AntGP (Antarctic Geoid Project), is chaired by TU Dresden. It aims at co-ordinating all efforts to improve the poor gravity coverage over Antarctica. The International Polar Year 2007/2008 will see many activities in this area.

In support of regional (German and European) geoid modelling several advances at the metrology side have been undertaken. BKG has revisited 30 absolute gravimeter sites, the first time since their establishment in the German gravity base network DSGN94. A quality of better than 5 mGal could be demonstrated. A digital zenith camera has been further developed at IfE into maturity. It is able to provide 0.1” accuracy in astronomic positions. Moreover, several gaps in the German gravity coverage, mostly over seas, have been covered by airborne gravimetry, cf. the section on Airborne Gravimetry. A high-precision long-range gravity calibration network has been established in a joint effort between IfE and IAPG (TU Munich) around the Zugspitze. The baseline covers a 2200 m height difference and a difference in gravity of 522 mGal.

Beyond regional geoid modelling purposes, it goes without saying that these activities also serve within the framework of GRACE and GOCE validation.

Absolute and Relative Gravimetry, Gravity Networks

H. WILMES[1], L. TIMMEN[2]

Several German universities, government agencies and observatories contributed to the activities described in the following. The major subjects were contributions to the global and national gravity reference frame, the determination and maintenance of gravity networks, the combination of gravity and height in dedicated networks, terrestrial gravity observations for the validation of the satellite gravity field models, the testing of improved instruments and the advancement of evaluation software.

Networks

Within a cooperation between the Institut für Astronomische und Physikalische Geodäsie (IAPG), München, and the Institut für Erdmessung (IfE), Hannover, a new absolute gravity base was established in the German Alps (mountains Zugspitze and Wank) during autumn season of 2004, a period with minimum snow coverage (TIMMEN et al. 2006a). This should ensure optimal environmental conditions with respect to the investigation of the uplift of the Alpine orogenesis and the deglaciation due to climate changes. The four stations cover a range in elevation of 2200 m and in gravity of 0.00522 m/s² (≡ 0.522 Gal). The accuracy of each station determination is assumed to be within ±20 to 40 nm/s². The main purpose of the new gravity net is to serve as a high-precision long-range gravity calibration line for the determination of linear and quadratic calibration terms of modern relative gravimeters.

In a continuation of this project IAPG and Bundesamt für Kartographie und Geodäsie (BKG) carried out field observations with its new field absolute gravimeter A10, first in February 2005 and again in July and September 2005 and successfully extended the network with repeat observations and additional sites. By observations in winter and summer seasons and further relative gravity measurements on valley and peak level of the calibration line at different epochs with in total three Scintrex gravimeters seasonal gravity changes due to the variation of snow masses could be visualized.

A general advancement can be seen in the observation of regional networks with precise FG5 instruments which then can be related to geometric height changes observed with continuous GNSS sensors on co-located sites:

Since 2003, absolute gravity measurements have been performed regularly by IfE in the Fennoscandian land uplift network covering Norway, Sweden, Finland and Denmark (TIMMEN et al. 2006b). In cooperation with the Nordic national geodetic agencies and research institutions and the BKG, terrestrial absolute gravimetry is applied to observe the postglacial land uplift due to the isostatic adjustment of the crust. Nearly all absolute stations are co-located with continuously observing GPS stations. From the comparisons between the participating instruments, an overall accuracy of ±30 nm/s² is indicated for a single absolute gravimeter and a single station determination. Thus, the gravity change due to the land uplift may be observed with an accuracy of ±10 to 20 nm/s² for a 5-year period. A main purpose of these terrestrial in-situ observations is to validate and test the GRACE results (ground-truth).

In the same region BKG complemented its time series of absolute gravity (AG) measurements started in 1993 with a fourth field campaign in 2003 on 10 sites. Most of these sites are also part of the European Combined Geodetic Network, ECGN, where precise connections with GNSS heights, levelling heights and tide gauge benchmarks are drawn. A further AG campaign was carried out by BKG in 2006 in cooperation with the Danish Space Centre on two sites in Denmark.

For monitoring the German gravity base network DSGN94, established in 1994 with 30 absolute sites, the first re-observation by BKG with FG5 measurements could be finished during the report period. It became evident that the detected gravity changes did not exceed the error margin from the initial measurements of ± 50 nm/s² (±5 μGal).

In Northern Italy repeated absolute gravity observations were taken by BKG on the ECGN site Medicina where the superconducting gravimeter is running and on additional stations where significant height and mass changes are expected due to geological or environmental influences.

As a contribution to the realization of an integrated geodetic reference network in Germany (GREF) with permanent GPS observations, connection to the first order levelling network and tide gauges where possible, also absolute gravity measurements with FG5 gravimeters were performed by BKG on now 16 additional permanent gravity sites. It is intended to revisit these sites in regular intervals of 2-3 years.

In the frame of the project GOCE GRAND II, BKG started A10 gravimeter field measurements on selected stations of the main gravity network DHSN of the German Federal

[1] Herbert Wilmes: Bundesamt für Kartographie und Geodäsie (BKG), Richard-Strauss-Allee 11, D - 60598 Frankfurt a.M., Germany, Tel. +49 - 69 - 6333 273, Fax +49 - 69 - 6 333 425, e-mail herbert.wilmes@bkg.bund.de

[2] Ludger Timmen: Gottfried Wilhelm Leibniz Universität Hannover, Institut für Erdmessung, Schneiderberg 50, D-30167 Hannover, Germany, Tel. +40 - 511 - 762 3398, Fax +49 - 511 - 762-4006, e-mail timmen@ife.uni-hannover.de

authorities. The purpose of these absolute gravity determinations is to identify systematic gravity offsets which might have influence upon the geoid modelling. The observations are also understood as a contribution to validate the satellite gravity field missions CHAMP, GRACE and GOCE by terrestrial gravity data.

The combination and evaluation works for the gravity reference network UEGN02 (Unified European Gravity Network 2002) was continued by the Bayerische Erdmessungskommission (BEK). The network includes more than 400 absolute and 33000 relative gravity observations at 1500 stations in a common adjustment. Problems for processing were lacking standardisation and minute data errors which required the development of appropriate tools for detection and which caused some delay. The progress was reported at several meetings (BOEDECKER et al. 2004, BOEDECKER 2006).

The two observatories Black Forest Observatory (University Karlsruhe and University Stuttgart) and Moxa (Friedrich-Schiller-Universität Jena) contributed high precision gravity time series (precise spring gravimeter at BFO and superconducting gravimeter at Moxa) which both were underlain by repeated absolute gravity measurements of different institutions. Moxa contributed to the Global Geodynamics Project (GGP) the global network of superconducting gravimeters (SG). At the Geodynamic Observatory Moxa special care was taken upon the determination of hydrological influences from the station environment. In 2004 a local gravity network for repeated measurements with field gravimeters was established in the station vicinity. The network consists of twelve observation points with six points on an EW-running profile with distances in the range of few to several tens of meters. The maximum elevation difference is 24 m. The network serves two purposes: It is used to determine what order of magnitude of gravity variations can still be detected with field instruments under optimal conditions for a small-scale network. The second purpose aims at the detection of hydrology-related gravity variations in the vicinity of the observatory, thus determining the applicability of this type of observation for studies of hydrological processes and the provision of constraints for hydrological water balances in a hilly area.

By repeated measurements with high quality 3-4 LCR-gravimeters significant changes in gravity differences could be obtained. The standard deviations obtained for the gravity differences between two observation points are in the order of 8 to 14 nm/s². The time-dependent variations in the differences reach up to 140 nm/s² (± 11-20 nm/s²) and correlate with changes in the hydrological situation.

The Institute of Physical Geodesy at the University of Technology Darmstadt focused their works upon tectonically active regions in of the Western part of the North Anatolian fault in Turkey (GERSTENECKER 2003, ERGINTAV et al. 2007) and the Merapi region in Indonesia (TIEDE et al. 2005a, 2005b) to interpret the time-dependent gravity changes.

BKG continues the observation series with the superconducting gravimeters at Wettzell, Bad Homburg, Medicina (Italy) and at Concepción (Chile). For Medicina an uninterrupted time series reached a length of 10 years in 2006. At all sites investigations have been started to relate the observed gravity changes with hydrological, atmospheric and height variations. BKG routinely contributes its SG time series to the Global Geodynamic Project (GGP).

Contribution to the International Gravity Reference System

BKG has taken responsibility for the national gravity reference of Germany and its integration in the international gravity system. This is achieved on the one hand side by the repeated four-yearly comparisons of AG within the frame of the International Comparative Campaigns at the Bureau International des Poids et Mesures BIPM, in Sèvres (France). BKG participated with the absolute gravimeter FG5-101 in 2005.

On the other hand, additional instrument comparisons were performed on selected gravity stations as supplementary measures and intermediate verifications for the purpose of securing the instrumental gravity standard. In November 2003, BKG participated in the regional comparison carried out at the station Walferdange (Luxembourg) with its absolute gravimeter FG5-301 (FRANCIS et al. 2005).

During the report period comparative measurements of FG5 gravimeters of BKG were conducted in Metsähovi (Finland) with the AG of the Central Research Institute for Geodesy, Aerophotogrammetry and Cartography (SNIGAiK), Moscow (Russia), in Strasbourg (France) with the FG5-206 of EOST and in Pecny (Czech Republic) with FG5-215 of VÚGTK.

The concept of the BKG gravity reference station Bad Homburg includes not only the operation of the superconducting gravimeter SG30, but there also exists the possibility to carry AG measurements on three different measuring pods. These are used in particular to monitor and compare the absolute gravimeters FG5 and A10 employed by BKG. Within the upgrading of the station Bad Homburg as a GREF station, and also as "ECGN Core Station", a permanent GPS receiver was installed on the building and tied into the local geodetic control network. Two groundwater level gauges complement the data series and provide information about hydrological changes at the site. The suggestion to use Bad Homburg as a regional comparison site for absolute gravimeters (WILMES, FALK 2006) was seized by several groups. Hence, the FG5 gravimeters of BKG were inter-compared with FG5-220 of IfE, Leibniz Universität Hannover in 2003, 2005 and 2006; with FG5-215 of the Research Institute for Geodesy, Topography and Cartography (VÚGTK), Prague (Czech Republic) in 2003 and 2005; with the FG5-230 of the Technical University Warsaw (Poland) in 2006 and with FG5-226 of the Norwegian University of Life Sciences, Ås in 2006.

Data evaluation methods

At the Institut für Erdmessung (IfE), Leibniz University Hannover, a new method has been developed to avoid uncertainties in the absolute gravity determination due to an uncertain vertical gravity gradient (TIMMEN 2003). The approach allows the use of a simple parabolic equation to evaluate the time/distance data pairs which are equally spaced in distance. Later, these g-determinations have to be corrected for the vertical gravity gradient using the effective measurement height. Even in extreme cases, unknown non-linearities in the vertical gravity gradient do not significantly affect the results of the absolute gravity determination.

At IfE, an improved atmospheric mass flow reduction for terrestrial absolute gravimetry is applied for all FG5 measurements with geodynamic objectives. The attraction and deformation effects for a local (spherical distance ≤ 1°), regional (≤ 10°), and global (≤ 180°) zone with corresponding resolutions of 0.01°, 0.2°, and 1.125° respectively, are calculated using the global data models from the European Centre for Medium-Range Weather Forecasts (ECMWF). The calculation procedure is explained in GITLEIN and TIMMEN (2006).

At BKG a new software tool has been developed for the combined analysis of superconducting gravimeter records together absolute gravimeter observations at the respective station. Thus, SG scale factor and SG instrumental drift can be determined. For the AG, information about the sensor stability can be derived or checked at the same time. This guarantees a high stability of the gravity reference system and a detailed monitoring of the contributing instruments in a rigorous comparison (WZIONTEK et al., 2006).

The Surveying and Mapping Agency of North Rhine-Westphalia has developed the relative gravimeter analysis software "Galileo" specialized upon the analysis of measurements with LCR gravimeters. The software handles the complete data flow from raw data to the storage of final gravity results based upon the favoured gravity system. "Galileo" considers all kinds of corrections like meteorological data, specifics of different gravity instruments, tide corrections and others.

(*http://www.lverma.nrw.de/produkte/programme/schwereauswertung/GALILEO.htm*)

Instrumentation

At the Institut für Erdmessung, Leibniz Universität Hannover, a detailed evaluation of the Scintrex Autograv CG-3M spring gravimeter no. 4492 was done with respect to the stability of the calibration, measurement accuracy and precision, drift behaviour, and gravity range dependency of the calibration factor. TIMMEN and GITLEIN (2004) present the results as obtained in regional, local and micro-gravimetric surveys. The achieved accuracies are in the order of ±10 to 100 nm/s^2 (±1 to 10 μGal). Over 3 years of surveys, the calibration was stable to an order of $1 \cdot 10^{-4}$ at least. No instability could be proven. Within a total range of almost 0.015 m/s^2, no gravity range dependence was found.

Within the reporting period, BKG continued the application of A10 gravimeters for field campaigns. In cooperation with IAPG München, the BEK and Bundesamt für Eich- und Vermessungswesen (BEV) Vienna (Austria) absolute observations with A10 were carried out at selected Alpine mountain peaks. The measuring instrument showed good performance during these test observations. Both A10 instruments of BKG were updated at the manufacturer and are in use in field campaigns on stations of the German gravity network since 2006.

At the site of the TIGO Fundamental Station in Concepcion (Chile) the superconducting gravimeter RTC038 operates since November 2002 (WILMES et al. 2006). The data series contributes to the monitoring of the gravity conditions and reflects mass variations in the surroundings of the station. In 2006 the absolute gravimeter FG5-227 of BKG was prepared for installation in parallel to the SG, and for this purpose equipped with a remote control interface accessible via internet.

After testing FG5-227 at the station Bad Homburg and relating to the international reference system, the instrument was installed Concepcion in spring 2006. Observations are initiated weekly; they confirm the strong yearly gravity variations in the order of more than 300 nm/s^2 (30 μGal) recorded with the superconducting gravimeter at the site.

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Airborne Gravimetry

G. BOEDECKER[1], U. MEYER[2]

1. Introduction

Airborne gravimetry developed in the past decades as to provide a more efficient observation technique compared to conventional ground observations and a higher spatial resolution than satellite methods. Currently, the spatial resolution at the level of one mGal[3] is of the order of 3…8 km; the aim is 1 mGal/1 km. The gravimeter sensor utilises a spring-mass accelerometer to sense the total acceleration **a**. Gravity **g** is recovered by subtracting the inertial acceleration **b**, derived from GNSS positioning, i.e. **g** = **a** –**b**. Both observation techniques for **a** and **b** as also the problems of data fusion, i.e. reference frame transformations and system fit, require further developments. Classical airborne gravimeters use one vertical sensor mounted to a gyro stabilised platform and hence deliver *scalar* values; new developments are also dealing with gravity *vectors* from a triad of accelerometers.

This report will restrict to airborne *gravimetry* with conventional sensors, hence we shall not be dealing with e.g. atom interferometers for gravimetry nor with gradiometers.

Airborne gravity lends itself for data fusion with ground gravity, satellite gravimetry and topographic-isostatic data. The gravity (details) attenuation with height and relations of the continuous field to discrete data require further studies driven by applications and increasing data availability.

2. System development

The Federal Institute for Geosciences and Natural Resources (BGR), Hannover, was using a platform gravity meter system KSS31 of 'Bodenseewerk Geosystem' for marine gravimetry since 1984. Modifications for airborne gravimetry required raw data recording, improved platform control, sensor sealing to air pressure variations, weight reduction etc.

Four Novatel OEM4 L1/L2 GPS receivers were acquired for kinematic positioning and inertial acceleration determination. After dynamical ground tests of the whole system on an airstrip, test flights out of Münster/Osnabrück followed in November 2003, showing the need for improvements of navigation and platform data (HEYDE, KEWITSCH 2004, 2005; MEYER, HEYDE 2004). Therefore, a Novatel SPAN INS/GPS integrating system was added. In cooperation with BGGS (successor of 'Bodenseewerk Geosystem', see above) a modul for platform angular error observations was developed. Also accounting for horizontal accelerations, the gravity effects from platform misleveling can be corrected now.

After these system improvements, four flight profiles were flown out of Münster/Osnabrück in May 2005, showing very satisfactory results despite rough air conditions (HEYDE, KEWITSCH 2006 a/b). Successful helicopter test flights in 2006 demonstrated e.g. the benefit of a smooth and steady flight path.

The Institute of Flight Guidance (IFF) of the Technical University of Braunschweig had acquired a Chekan-A 2-axis platform gravimeter of Elektropribor, St. Petersburg, Russia, several years ago (CREMER 2003, SCHÄNZER 2003). This instrument has been upgraded in the past years. E.g., a ring laser azimuth gyro for an analytical 3rd axis was added and via a Kalman filter developed for the whole system including also GPS states the misalignment was reduced considerably and dynamic capabilities were improved. For altitude determination, a precision barometric 'statoscope' of small range and high resolution has been refined by instrumental and modelling measures to an accuracy level commensurate with GNSS but with different characteristics which makes a fusion very attractive. Different GNSS kinematic positioning scenarios were studied. A patented complementary airborne gravimeter real time feedback system warrants high accuracies. Test flights with IFFs Dornier 128-6 demonstrated an anomaly accuracy / resolution of 1 mGal / 5 km. See CREMER, STELKENS (2003), STELKENS et al. (2003-2006).

The Institute of Geodesy and Navigation (EN) at the University of Federal Armed Forces München at Neubiberg uses a commercial strapdown inertial navigation System (SDINS) system Sagem Sigma 30 equipped with triads of ring laser gyros and high precision accelerometers for airborne vector gravimetry. The focus of own activities is on algorithms including filters both for the total acceleration and for the kinematic acceleration signal. E.g., the aircrafts vibrations induced on the SDINS is mitigated by customized software instead of classical shockmounts. This facilitates aircraft integration and avoids further transfer function complexities. Kinematic accelerations were determined directly from GNSS receiver output without positioning detour. The resulting lower noise level allows

[1] Gerd Boedecker: Bayerische Kommission für die Internationale Erdmesung / BEK, Alfons-Goppel-Str. 11, D - 80539 München, Germany; Tel. +49 - 89 - 23031 1212, e-mail: boe@bek.badw-muenchen.de

[2] Uwe Meyer: Bundesanstalt für Geowissenschaften und Rohstoffe / Aerogeophysik, Stilleweg 1, D - 30655 Hannover, Germany, Tel. +49 - 511 - 643-3212, e-mail: U.Meyer@bgr.de

[3] 1 mGal = 1 •10^{-5} ms

shorter integration times and hence a higher spatial resolution. The system showed good resolution and accuracy (2-3 mGal / 1 km) at several test flights. See KREYE (2006), KREYE, HEIN (2003, 2004), KREYE et al. (2003, 2004, 2006).

For an overview of GNSS use for airborne gravimetry, see HEIN, KREYE, NIEDERMEIER, HEYEN, STELKENS-KOBSCH, BOEDECKER (2006). Future system innovations will include the use of Galileo.

The 'Bayerische Erdmessungskommission (BEK)' at the Bavarian Academy of Sciences and Humanities, München, embarked on the construction of an airborne strapdown vector gravimeter from accelerometers, gyros, and signal processing components. This approach offers the opportunity for detailed optimisation and accounting for classical gravimetric techniques such as temperature control and optimised vibration damping (BOEDECKER, STÜRZE 2004). The current (patented) prototype SAGS4 e.g. uses an attitude determination by integrating fibre optical gyros and a GPS multi antennae system for enhanced long range stability (BOEDECKER 2005). Part of the sensor cluster are high rate GPS receivers sampling at 50 /s for high resolution and mm accuracy (STÜRZE, BOEDECKER 2004). The accelerometer noise is at the level of 1 mGal. Test flights with various aircraft provided operational experiences. A lift constructed for dynamic calibration provides transfer functions for the accelerometers as also for kinematic GNSS observations and thus enables a good system fit (BOEDECKER, STÜRZE 2006).

The aforementioned groups of IFF, EN and BEK as also the 'Aerodata Flugmesstechnik GmbH', Braunschweig, did some coordinated research and joint test flights in 2002-2005 in the framework of the BMBF 'Geotechnologien-programm'.

3. Combination techniques, upward/downward continuation

The different altitudes of gravity observations – ground, aircraft, satellite –, discretization and irregularity of topographic-isostatic masses pose a number of problems:

At the 'Institut für Theoretische Geodäsie' of Bonn university, different downward continuation methods are compared and the impact of regularization of airborne gravimetry data and optional postprocessing filtering is addressed by MÜLLER, MAYER-GÜRR (2003) for simulated and real data. The gravity field effects of the topographic-isostatic masses represent important information on the high-frequent part of the gravity field. MAKHLOOF et al. (2006), MAKHLOOF, ILK (2005, 2007a,b) and MAKHLOOF (2007) address the physical-mathematical basics of the classical topographic-isostatic models. These models are formulated mathematically with the emphasis on a spherical approximation from the modelling point of view and on the observables of airborne gravimetry and modern satellite techniques from the application point of view. Besides the representation of the topographic-isostatic mass effects by volume integrals, discretized by spherical volume elements, the representations by series of spherical harmonics and space localizing base functions are considered. Detailed formulae are presented for the direct and secondary indirect topographical effects as well as for the primary indirect topographical effect in the geoid heights for the different representations. A specific topic in some articles is the determination of the so-called far-zones based on an approach which goes back to a formulation by Molodenskii. Extended test computations give an impression of the size and distribution of the various effects for regional and global test areas with different resolutions of the topography.

In the framework of a cooperation between the 'Lehrstuhl Physikalische und Satellitengeodäsie' at Karlsruhe university and the University of Calgary, NOVAK et al. (2003) study geoid computations from airborne gravity data combined with global gravity models and ground data; this includes the downward continuation problem. After numerical tests with synthetic data, the procedure is applied to an airborne gravity data set observed in a test area (of about 100 km x 100 km, ~1mGal / 5 km) in Canada by Sander Geophysics Labs modern AIRGrav platform airborne gravimeter. The fusion / comparison with global gravity models and/or ground data demonstrates the progress by airborne gravimetry. NOVAK et al. (2003) evaluate the band-limited topographical effects in airborne gravimetry: The spectrum of airborne gravity observations (at height) is limited i) because of the attenuation of the gravity signal higher frequencies with increasing distance from the attracting irregular masses and ii) because of the low pass filtering of airborne gravity observations necessary mainly because of the aircrafts dynamics. Consequently, the topographical effects along the flight lines are also filtered by the same low pass filter. The resulting band limitation permits the application of global spherical harmonics for the topographical reduction which would not be possible for ground gravity values. Numerical tests are based on 3"x3" DEM in the Canadian Rockies using Helmerts reduction.

4. Observation campaigns / commercial usage

The Federal Agency for Cartography and Geodesy (BKG) and the Danish National Space Center (DNSC) carried out an airborne gravimetry campaign in the Southwest Baltic Sea and neighbouring land areas (~53.5°-55.5° N, ~8°-15° E), using a LaCoste & Romberg airborne gravimeter (S-38). The observations were flown with a King Air B200 aircraft of COWI company on 23 parallel flight tracks along and 4 across with a total of 10,000 km within 45 hours in October 2006. Partly, a Riegl laser scanner was also used. In summer 2007, a similar campaign is planned for the North Sea. (Reported by U. SCHÄFER, BKG; to be published 2007).

The Alfred-Wegener-Institute (AWI), Bremerhaven, has carried out a number of airborne gravimetry campaigns in Antarctica for the 'Validation, Densification and Interpretation of Satellite Data for the Determination of Magnetic Field, Gravity Field, Ice Mass Balance and Structure of the Earth Crust in Antarctica, Utilizing Airborne and Terrestrial Measurements' (VISA) on the inland ice sheet of the

Dronning Maud Land 15˚W-17˚E, 70˚-79˚S: 2002-03: VISA II; 2003-04: VISA III; 2004-05: VISA IV. VISA is a joint project of AWI and the 'Institut für Planetare Geodäsie (IPG)' of the Technical University Dresden, funded by the German Research Foundation (DFG). These activities were continued in the framework of the 'West-East Gondwana Amalgamation and its Separation' (WEGAS) in the eastern Dronning Maud Land and western Enderby Land, 35˚-45˚E, 65˚-73˚S over the inland ice sheet and the offshore ocean area. The flight track spacing was 10 km, except close to the Russian overwintering station, where it was 20 km. Results will be published soon, e.g. in forthcoming dissertation (Reported by D. STEINHAGE, AWI). See also NIXDORF et al. (2004).

The IPG is also engaged in the IAG Antarctic geoid project, for which airborne gravimetry is to play a major role for filling the gaps in gravity data coverage. See SCHEINERT (2005), MÜLLER et al. (2004). Also, airborne gravity on board the new German "High Altitude and Long Range Research Aircraft" (HALO) will be put forth by Scheinert via the respective geoscientific user group; see MEYER, U., STEINHAGE, SCHEINERT, BOEDECKER, AND LAUTERJUNG (2005).

An airborne gravity survey of an 260 km x 150 km area in the German sector of the North Sea with 5 km profile spacing at 2000 ft flight altitude and 190 km/h speed is scheduled for May 2007 by BGR (c.f. sec. 2).

Based on previous developments and experiences at IFF Braunschweig, c.f. section 2, a spin-off company 'Gravionic' for airborne gravimetry services starts in 2007, supported by European funds (EFRE/ESF). A Russian Chekan-AM gravimeter, follower of the above mentioned Chekan-A, was acquired; the above mentioned unique feedback patent is also part of the company's portfolio. Flight tests in February 2007 were very promising; cost optimisation is underway. Services for exploration and tectonic geophysics as also for geoid determinations in the air and on the seas will be offered soon (reported by STELKENS-KOBSCH).

5. Summary and outlook

While the number of airborne gravimetry observation activities is increasing employing decades-old technology, further system developments towards km resolution vector airborne gravimetry is progressing at a low pace due to insufficient support compared to e.g. satellite methods. The progress of data fusion techniques also including topographic-isostatic data appears adequate in view of the increasing availability of satellite and ground topography data. In view of the basic limitations in resolution of satellite gravimetry, performance advantages compared to ground techniques and the increasing need for dense gravity coverage, further methodological and operational progress for airborne gravimetry can be expected.

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Gravity Field Satellite Missions

F. FLECHTNER[1], T. GRUBER[2]

Introduction

Since the launch of the German CHAMP (Challenging Mini-Satellite Payload for Geophysical Research and Application) satellite mission in July 2000 and the American-German Gravity Recovery and Climate Experiment (GRACE) in March 2002 the knowledge of the Earth gravity field has been revolutionized. Today, the static gravity field can be determined with unprecedented accuracy and, for the first time, temporal variations at longer wavelengths up to degree and order 35 to 40 can be monitored allowing the quantification of mass distribution and mass variations in the system Earth. As a result of the 5-years GRACE operation, important information about the continental hydrological cycle, the ice mass balance in Greenland and Antarctica, the steric and mass-related contribution to sea level rise or the inter-annual ocean mass variation could already be obtained.

While CHAMP results are based on high-low and for GRACE additionally on low-low satellite-to-satellite tracking data, only the long-to-medium wavelengths roughly up to degree and order 50 and 100, respectively, can be observed with sufficient accuracy. The European gradiometric mission GOCE (Gravity and Ocean Circulation Explorer), due for launch end of 2007, will provide precise information about the medium to short-wavelengths parts of the gravity field up to a spherical harmonic degree of 200-250. Consequently, a combination of GRACE and GOCE will provide a homogeneous multi purpose satellite-only gravity field model of unprecedented quality.

Detailed information on global gravity field and geoid modelling as well as on temporal gravity field variations can be found in dedicated chapters in the Commission 2 report. There, also a more detailed list of CHAMP, GRACE and GOCE related papers is given.

In Germany, the GEOTECHNOLOGIEN research program of the federal government and a Special Priority Program "Mass Transport and Mass Distribution in the Earth System" funded by the German Research Foundation DFG has enabled and will bring considerable progress in research related to CHAMP, GRACE and GOCE.

Status of gravity field missions

In July 2007 CHAMP is in orbit for exactly 7 years. Thanks to two orbital raise manoeuvres in 2002 and one in 2006 the current satellite altitude is still about 370 km. All instruments, except the Digital Ion Driftmeter DIDM, are producing high quality data for gravity and magnetic field analysis and atmospheric and ionospheric research. The orbital decay due to solar activity predicts a remaining life time at least up to end of 2008.

GRACE has celebrated its fifth birthday in March 2007. The predicted lifetime calculated from gas consumption, thruster activations and solar activity is at least 2011. All instruments are producing nominal gravity and occultation data. The latter are already operationally assimilated at UK Metoffice since September 2006. To mitigate the risk of loss of thermal control over the K-Band horn (and subsequent generation of spurious K-Band range signal) due to atomic oxygen exposure the GRACE satellites have been successfully switched in December 2005.

The GOCE mission is scheduled for launch in December 2007. Due to the extraordinary complexity of the satellite and instrument systems the launch has been delayed by approximately 1,5 years (originally it was scheduled for August 2006). As of today all instruments have been finalized and most of them have been integrated on the platform. After the final integration will be completed the remaining satellite platform and instrument tests will be performed, before it will be shipped to Plesetzk/Russia for launch.

The most recent information about the status of the missions CHAMP and GRACE and about the progress of preparations of GOCE can be found on the Web sites of GFZ Potsdam (for CHAMP and GRACE), of the University of Texas at Austin (for GRACE), and of the European Space Agency Living Planet Programme (for GOCE). Results from CHAMP's first five years in orbit were given in REIGBER et al. (2005). TAPLEY et al. (2007) presented specific details on the GRACE mission status. The design and operation of the Integrated System and Data Center ISDC which is the European archive for CHAMP and GRACE data products was treated in RITSCHEL et al. (2006). The multi-mission raw data center for CHAMP and GRACE was described in MISSLING et al. (2005).

[1] Frank Flechtner: GeoForschungsZentrum Potsdam (GFZ), c/o DLR, D - 82234 Wessling, Germany, Tel. +49 - 8153 - 28-1735, Fax +49 - 8153 -288-1297, e-mail flechtne@gfz-potsdam.de

[2] Thomas Gruber: Institut für Astronomische und Physikalische Geodäsie, Technische Universität München, Arcisstraße 21, D - 82290 München, Germany, Tel. +49 - 89 - 289-23192, Fax +49 - 89 - 289-23178, e-mail thomas.gruber@bv.tu-muenchen.de

Development of sensor analysis and gravity field determination, validation and calibration techniques

In Munich, a simulation tool for the integrated sensor analysis of CHAMP, GRACE and GOCE instrument data has been developed, optimized and used to analyze real CHAMP and GRACE mission data (FROMMKNECHT et al. (2003, 2006), FACKLER (2005)). The combination of star sensor and accelerometer data was investigated by OBERNDORFER and MÜLLER (2003). WERMUTH et al. (2006) performed GOCE mission simulation and semi-analytical gravity field analysis for SGG and SST data.

The determination of highly-precise orbits for the Low Earth Orbiters based upon GPS and SLR observations is an important prerequisite for gravity field recovery. Dynamic model orbits from combined LEO and GPS data were generated by KÖNIG et al. (2005) while kinematic precise orbit determination was described in SVEHLA and ROTHACHER (2005) and SVEHLA and FÖLDVARY (2006). KROES et al. (2005) and KOHLHASE et al. (2006) investigated precise GRACE baseline determination using GPS data.

While the operational global gravity field products of the CHAMP and GRACE Science Data Systems at GFZ Potsdam are based on dynamical orbit analysis of daily arcs (REIGBER et al. (2003a, 2003b, 2003c, 2005), SCHMIDT et al. (2006)) other groups started to analyse and validate the measurement data with alternative methods and also on regional scales. ILK et al. (2005) and MAYER-GÜRR et al. (2005, 2006) performed gravity field recovery and validation by analysis of short arcs of CHAMP and GRACE. The usefulness of the energy balance method for gravity field determination and validation was shown by several authors (ILK (2003), VISSER et al. (2003), ILK and LÖCHER (2005), FÖLDVARY et al. (2005), GERLACH et al. (2003a, 2003b), REUBELT et al. (2006), or LÖCHER and ILK (2007)). Regional gravity field solutions based on spherical wavelet and base functions were presented by ILK et al. (2007) and SCHMIDT et al (2006, 2007). The concept of the gravity space approach was demonstrated by AUSTEN and KELLER (2007). FENGLER et al. (2004a, 2004b) derived CHAMP and GRACE gravity field solutions by multiscale methods. Gravitational field modelling from CHAMP-ephemeredes by harmonic splines and fast multipole techniques was described by GLÖCKNER (2003). The modelling of regional and temporal gravity field solutions using wavelet modelling was shown by FENGLER et al. (2005, 2007) and FREEDEN and SCHREINER (2005). Different gravity field determination procedures applied to CHAMP data were compared by WERMUTH et al. (2004). Sneeuw reported on the space-wise, time-wise, torus and Rosborough representation in gravity field modelling.

BOSCH (2005) used the EIGEN-GRACE02S gravity field model to investigate defectiveness of marine gravity data and KLOKOCNIK et al. (2005) evaluated the accuracy of the EIGEN-1S and -2 CHAMP derived gravity field models by satellite crossover altimetry. A high resolution global gravity field model from combination of CHAMP and GRACE satellite mission and surface data called EIGEN-CG01C was presented by REIGBER et al. (2006).

Preparations for GOCE

Preparations for GOCE data analysis have been performed on various levels. DENKER (2003), DIETRICH et al. (2004), MÜLLER et al. (2003, 2004), BOUMAN et al. (2005), TOTH et al. (2005) and JARECKI et al. (2006) investigated methods to calibrate and validate the GOCE gradiometer data. The development and status of the GOCE High Level Processing Facility (HPF), which is in charge for the GOCE gravity field determination was described in RUMMEL et al. (2004), GRUBER et al. (2006) and KOOP et al. (2007). PAIL et al. (2007a, 2007b) developed tools for HPF GOCE quick-look gravity field analysis, which is designed for monitoring the overall GOCE performance as part of the HPF activities. The correct use of GOCE level-2 products was treated by GRUBER et al. (2007). The German GOCE project bureau at Technical University of Munich contributed since 2001 to a coordinated preparation of GOCE data analysis and applications in Earth sciences.

Outcome and further Planning

As a result of the enormous success of CHAMP and GRACE and in expectation of the GOCE mission results a Special Priority Program SPP "Mass Transport and Mass Distribution in the Earth System" has been proposed by ILK et al. (2004, 2005) and finally accepted by the German Research Foundation DFG for the period 2006 till 2011. FLURY and RUMMEL (2004) introduced the goals of the SPP at a GOCE user workshop.

The need and design of future follow-on gravity field missions to derive continuous and highly precise time series of gravity field variations for Earth system monitoring was discussed in BEUTLER et al. (2003), AGUIRRE-MARTINEC and SNEEUW (2003), FLURY and RUMMEL (2005a, 2005b) and SNEEUW et al. (2005).

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Global Gravity Field Modelling

T. GRUBER[1]

Introduction

In the reporting period from 2003 to 2007, global gravity field modelling work in Germany was focused on the exploitation of data from the German CHAMP and the US/German GRACE missions as well as on the preparations for the data analysis of the GOCE gradiometry mission by ESA. From the Champ mission, launched in July 2000, a multi-year data set became available enabling fundamental investigations on classical and new techniques for global gravity field modelling. These techniques, as well as new approaches specifically developed for the GRACE data analysis, were applied to the newly available inter-satellite tracking data from this mission. In 2005 data from the GRACE mission (launched in 2002) were released and since then extensively used by different groups in Germany in order to determine the static and time variable gravity field. For preparing the analysis of the gradiometer data from the GOCE mission (to be launched end of 2007) extensive work has been performed in various projects by a number of university and research institutes all over Germany. This preparatory work will enable these groups to quickly use this new data type for global gravity field modelling. In context with these gravity field satellite missions the issue on calibrating and validating the instruments, as well as the validation of the derived global gravity field models becomes more and more emerging. Several studies and attempts on this issue have been performed. The following chapters provide short summaries on modelling techniques, global gravity field models and model validation. They shall provide an overview of the work performed in this research field over the last four years. A few additional remarks about future prospects of global gravity field modelling are made in the final chapter. An extensive list of references is provided at the end.

Modelling Techniques

General Aspects: With the new satellite missions, there are available different data types to observe the gravity field from space (e.g. high-low SST, low-low SST, gravity gradients). A general overview about gravity field analysis techniques based on the different observables is given in BEUTLER et al. (2003), RUMMEL (2003a) and FLURY et al. (2006). An overview about the application of Earth gravity fields in different disciplines is given in RUMMEL (2005), ILK et al. (2004) and ILK et al. (2005d). Various dedicated geodetic techniques for gravity field determination and analysis are addressed by several authors. See papers by AUSTEN & KELLER (2007), BÖLLING & GRAFAREND (2005), FÖLDVARY & WERMUTH (2005b), HECK (2003a) (20034a), HECK & SEITZ (2003b) (2007), HECK & WILD (2004b), ILK (2003a), ILK et al. (2007), KABAN et al. (2004) (2005), KELLER & SHARIFI (2005), KUHN & SEITZ (2004), MARINKOVIC et al. (2003), MEYER (2006), NOVAK et al. (2005), REUBELT et al. (2003a) (2003b), SCHÄFER et al. (2003), SCHNEIDER (2004) (2005a) (2006) and SCHNEIDER & CUI (2005b), SEITZ (2003), SHARIFI & KELLER (2005), SNEEUW (2003a), SVEHLA & ROTHACHER (2005), SVEHLA & FÖLDVARY (2006), TSCHERNING & HECK (2005), TSOULIS (2005). Wavelet (or multiscale) techniques for gravity field modelling are addressed by FENGLER et al. (2004c), FREEDEN et al. (2003a, 2003b), FREEDEN & MICHEL (2004), FREEDEN & SCHREINER (2005), FREEDEN & MAYER (2006), KELLER (2004), SCHMIDT M. et al. (2004, 2005, 2007). A summary on fundamental parameters and standards is given in GROTEN (2004).

CHAMP: With the availability of a continuous multi-year time series of GPS observations from a low Earth orbiter to the GPS constellation dedicated analysis techniques became possible. For a summary see MAYER-GÜRR et al. (2005b) and WERMUTH et al. (2004). One can distinguish between the classical orbit perturbation approach used by REIGBER et al. (2003a) (2003b) (2003c) (2005b) (2006a), multiscale techniques applied by FENGLER et al. (2004b, 2005), the energy balance approach used by FÖLDVARY et al. (2005), GERLACH et al. (2003a) (2003b), SNEEUW et al. (2003b) (2005a), VISSER et al. (2003), semi-analytical computations performed by FÖLDVARY et al. (2003), short arc techniques used by ILK et al. (2005a), MAYER-GÜRR et al. (2003a), MAYER-GÜRR (2006), the accelerations approach applied by REUBELT et al. (2006), and harmonic splines and multipole techniques done by GLOCKNER (2003). Several papers also deal with the determination and application of kinematic orbits for gravity field modelling. See GÖTZELMANN et al. (2006), SVEHLA & ROTHACHER (2005) and SVEHLA & FÖLDVARY (2006).

GRACE: Similar as for CHAMP also GRACE data have been analyzed intensively and gravity field solutions have been determined by different methods. As the GRACE observation system is much more complicated some studies about sensor performance have been performed in parallel, see FACKLER (2005), FROMMKNECHT et al. (2003) (2006). Gravity field determination using GRACE data has been done by applying the following techniques: Classical orbit perturbation theory, see FLECHTNER (2003), FLECHTNER et al. (2006), REIGBER et al. (2005a), SCHMIDT R. et al. (2003, 2006), TAPLEY et al. (2007); Short arc technique,

[1] Thomas Gruber: Institut für Astronomische und Physikalische Geodäsie, Technische Universität München, Arcisstraße 21, D-82290 München, Germany, Tel. +49-89-289-23192, Fax +49-89-289-23178, e-mail Thomas.Gruber@bv.tu-muenchen.de

see ILK et al. (2005b), MAYER-GÜRR et al. (2006), MAYER-GÜRR (2006); Integration approach, see NOVAK et al. (2006); Multiscale modelling, see FENGLER et al. (2004a) (2005, 2007), SCHMIDT M. et al. (2006). Several solutions have been computed from the GRACE data (see chapter on global models).

GOCE: As the GOCE mission is not yet in orbit, work concentrated on preparations for using the new type of gravity gradient observations for global gravity field modelling, on calibration & validation of the GOCE gravity gradient data and on required computational efforts for a global model up to degree and order 250. For more details on the GOCE mission and products, see GRUBER & RUMMEL (2006), GRUBER et al. (2006) (2007), KOOP et al. (2007), RUMMEL et al. (2003b) (2004) (2007). The major work was focused on using GOCE data for gravity field recovery. Different approaches as well as techniques to filter the band-limited gradient observations have been developed and implemented. For more details see: ABRIKOSOV & SCHWINTZER (2004), ABRIKOSOV et al. (2006) (2007a) (2007b), BAUR & SNEEUW (2007), EICKER et al. (2005) (2006), FÖRSTE et al. (2007), KARGOLL (2003, 2005), MAYER-GÜRR et al. (2003b) (2003c), PAIL et al. (2005) (2007a) (2007b) (2007c), SCHUH W.D. (2003a) (2003b), SCHUH W.D. et al. (2007), WERMUTH et al. (2003, 2006), WILD & HECK (2004) (2005). As the computational effort to determine a GOCE gravity field solution is extraordinary, another focal point was the derivation and implementation of efficient algorithms. More details can be found in: ALKHATIB (2003), ALKHATIB & SCHUH (2007), AUSTEN et al. (2006), AUSTEN & KELLER (2006), BAUR & GRAFAREND (2005, 2006), BAUR et al. (2006), BAUR & KUSCHE (2007), BOXHAMMER (2003) (2006), BOXHAMMER & SCHUH (2006), GUNDLICH et al. (2003), KOCH et al. (2004), KOCH (2005). Gravity gradients observed in space by the GOCE mission are internally and externally calibrated. The calibration is crucial for the quality of the final global gravity field models. Several papers address methods and tools either to calibrate or to validate the observed gravity gradients. See: BOUMAN et al. (2005), DENKER (2003), DENKER et al. (2003), DIETRICH et al. (2004), JARECKI & MÜLLER (2003), JARECKI et al. (2006), MÜLLER (2003a), MÜLLER et al. (2003b) (2004), STUMMER (2006), TOTH et al. (2005a) (2005b), WOLF et al. (2003) (2004) (2005), WOLF (2006).

Global Models

The following global gravity field models have been published by groups in Germany (some in cooperation with other international partners):

- EIGEN-2 : CHAMP, GeoForschungsZentrum Potsdam, REIGBER et al. (2003d);
- EIGEN-CHAMP03S: CHAMP: GeoForschungsZentrum Potsdam, REIGBER et al. (2005b);
- EIGEN-GRACE02S: GRACE, GeoForschungsZentrum Potsdam, REIGBER et al. (2005a);
- EIGEN-CG01C: GRACE & surface data, GeoForschungsZentrum Potsdam, REIGBER et al.(2006b);
- EIGEN-CG03C: GRACE & surface data, GeoForschungsZentrum Potsdam;
- EIGEN-GL04S: GRACE, LAGEOS, GeoForschungsZentrum Potsdam;
- EIGEN-GL04C: GRACE, LAGEOS & surface data, GeoForschungsZentrum Potsdam;
- ITG-CHAMP01: CHAMP, Universität Bonn, MAYER-GÜRR et al. (2005a), ILK et al. (2005a);
- ITG-GRACE02s : GRACE, Universität Bonn, MAYER-GÜRR et al. (2007);
- SWITCH-03: CHAMP, Technische Universität Kaiserslautern, FENGLER et al. (2004b);
- TUM-1s: CHAMP, Technische Universität München, GERLACH et al. (2003a);
- TUM-2sp: CHAMP, Technische Universität München, FÖLDVARY et al. (2005);
- TUM-2s: CHAMP, Technische Universität München.

Model Validation

The validation of global gravity field models by means of independent data and observations becomes more and more important, because the mission data from CHAMP, GRACE and GOCE provide fields with unprecedented accuracy. In opposite, gravity field solutions from these missions can also be applied for validating ground data. GRUBER (2004) summarizes classical concepts, which can be applied for validating satellite derived global gravity field models. ILK & LÖCHER (2005c), LÖCHER & ILK (2005) (2007) apply energy balance equations for validating gravity field models and orbits. KLOKOCNIK et al. (2005) and ROMANOVA et al. (2007) use satellite altimeter data via the crossover technique and ocean state estimation procedures, respectively, for validating global gravity field models by means of independent data over the oceans. Finally, ROLAND & DENKER (2003) (2005b) (2005c) and ROLAND (2005a) use global gravity field models for validating observed gravity data on ground. All methods require the application of filter techniques in order to enable the comparison of band-limited global models (by a truncated spherical harmonic series) to observed ground data containing the full signal.

Future Prospects

A few studies on the requirements and instrumentation of future gravimetry satellite missions have been performed during the reporting period. These studies were focused on the identification of the scientific requirements for the different science applications, see AGUIRRE-MARTINEC & SNEEUW (2003), FLURY & RUMMEL (2005) and SNEEUW et al (2005b). Further studies recently have been initiated, which will identify more details of potential future mission scenarios and possible instrumentation configurations.

During the next couple of years the analysis of the GRACE mission data as well the availability of the GOCE gravity gradients will drive the further development in this area. It can be expected that new sets of gravity field models either from GRACE or GOCE only and from combinations of both with unprecedented accuracy and spatial resolution will become available. These fields will finally represent the baseline for any further development and for the definition of potential future gravimetry missions.

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Regional Gravity Field Modelling

H. DENKER[1]

1. Modelling Techniques

Fundamentals of gravity field modelling are described in the textbook published by TORGE (2003), while the textbook from FREEDEN and MICHEL (2004) focuses on the application of multiscale techniques in potential theory. Moreover, multiscale techniques were studied with regard to geoid modelling (FEHLINGER et al. 2007, FENGLER et al. 2004a, FREEDEN et al. 2007, FREEDEN and SCHREINER 2006, KUROISHI and KELLER 2005), global gravity field modelling (FENGLER et al. 2004b, HESSE 2003), and temporal gravity field variations (FENGLER et al. 2005 and 2007). In addition, advanced gravity field modelling topics and results are presented in the dissertation theses from GERLACH (2003), HIRT (2004), ROLAND (2005) and WOLF (2007).

Different approaches for terrain and mass reductions are discussed in HECK and SEITZ (2007) and KUHN and SEITZ (2005). The use of terrain reductions in connection with satellite gradiometry is investigated in HECK and WILD (2005) and WILD and HECK (2004 and 2005). Band-limited topographic effects for application in airborne gravimetry and subsequent geoid determination are studied in NOVAK et al. (2003a and 2003b). High-frequency terrain effects are also evaluated in VOIGT and DENKER (2007). Helmert's methods of condensation are analyzed in HECK (2003) and TSCHERNING and HECK (2005). Density variations are estimated from gravity and elevation data in RÓZSA (2003), while MLADEK (2006) discusses hydrostatic isostasy. An evaluation of the global SRTM and GTOPO terrain data sets in Germany is presented in DENKER (2005a). Problems in connection with vertical reference frames are analyzed in HECK (2004).

FLURY (2006) compared short wavelength spectral properties of gravity anomalies from various regions and derived a degree variance model for topographically reduced gravity anomalies. FINN and GRAFAREND (2003) constructed maps of ellipsoidal vertical deflections. Combined regional gravity field solutions were studied in EICKER et al. (2006), GITLEIN et al. (2005), KUROISHI and DENKER (2003), ROLAND and DENKER (2005b) and WOLF and KIELER (2007).

2. Observation Techniques

A digital transportable zenith camera system was developed and tested at the Institut für Erdmessung (IfE), Leibniz Universität Hannover (HIRT 2003 and 2004, HIRT et al. 2005B, HIRT and BÜRKI 2003 and 2006). Besides hardware improvements (HIRT and KAHLMANN 2004, KAHLMANN et al. 2004), refraction studies (HIRT 2006) and accuracy verifications (HIRT et al. 2004 and 2005a) were performed. Furthermore, the system was used in several observation campaigns in Switzerland (BÜRKI et al. 2005, HIRT and REESE 2004, MARTI et al. 2004, MÜLLER et al. 2004a) and Germany (HIRT et al. 2006 and 2007, FLURY et al. 2006). The results indicate an observational accuracy of about 0.1" for the astronomic positions.

3. Geophysical Investigations

A homogeneous Bouguer gravity map was published for the Rhine Graben in cooperation between the Leibniz Institute for Applied Geosciences (GGA-Institut), Hannover, and the Institut de Physique du Globe de Strasbourg (ROTSTEIN et al. 2006). Further regional data compilations and interpretations were realized for the Alps (ZANOLLA et al. 2006) and the Eifel region (RITTER et al. 2007). Local geophysical interpretations based on gravity observations were presented for maar volcanic structures in the Upper Lusatia region (GABRIEL 2003a, LINDNER et al. 2006, SCHULZ et al. 2005), in Bavaria (GABRIEL 2003b), for the UNESCO world heritage site Messel Pit (BUNESS et al. 2004, JACOBY et al. 2005, SCHULZ et al. 2005), and for a tuff chimney structure near Ebersbrunn, West-Saxony (KRONER et al. 2006). Gravimetric and geodynamic modelling was carried out in the Vogtland and NW-Bohemia region to study swarm earth quake activities (HOFMANN 2003, HOFMANN et al. 2003). A combined 3-D interpretation of gravity and aeromagnetic data, continental and marine seismic profiles, well logs and geological cross-sections was done for the northern Red Sea rift and Gulf of Suez (SALEH et al. 2006). Another field of investigation were Pleistocene valleys in northern Germany with emphasis on ground water related structures (GABRIEL 2006, GABRIEL et al. 2003, RUMPEL et al. 2006, THOMSEN and GABRIEL 2006, WIEDERHOLD et al. 2005).

Within the Collaborative Research Centre 526 "Rheology of the Earth – from the Upper Crust to the Subduction Zone" at the Ruhr-Universität Bochum, a study of the Earth's gravity field around Crete has given insight into the density structure of the Hellenic subduction zone (CASTEN and SNOPEK 2006, PRUTKIN and CASTEN 2007, SNOPEK and CASTEN 2006, SNOPEK et al. 2007). Computer aided gravity modelling was done by application of forward techniques and by direct inversion; new software was developed within the framework of the project.

Gravity data were archived in the Geophysical Information System, maintained by the GGA-Institut (KÜHNE 2005 and 2006, KÜHNE et al. 2003). Actually, the Geophysical

[1] Heiner Denker: Institut für Erdmessung, Leibniz Universität Hannover, Schneiderberg 50, D-30167 Hannover, Germany, Fax: +49 - 511 - 7622796, Tel. +49 - 511 - 762-2796, e-mail: denker@ife.uni-hannover.de

Information System contains 281,000 gravity points covering entire Germany and border-zone areas to neighbouring countries. 157,000 data points belong to companies from the German hydrocarbon industry. The system is open to the public via the internet.

4. Projects and Results

Within the framework of the "European Gravity and Geoid Project (EGGP)", a project within Commission 2 of the International Association of Geodesy (IAG), several new European geoid and quasigeoid models were derived and a final version shall be presented at the IUGG General Assembly 2007 in Perugia. The project (also known as CP2.1) is chaired by H. DENKER, IfE, Hannover. Progress reports were given anually at scientific meetings in Porto 2004 (DENKER et al. 2005, DENKER 2005b), Austin 2005 (DENKER 2005d), and Istanbul 2006 (DENKER et al. 2007). Further informations related to the EGGP can be found in DENKER et al. (2003a and 2004) and DENKER (2004, 2006a, 2006b). Due to the confidentiality of many data sets, only one data and computing center was set up at IfE in Hannover. The presently available results indicate an accuracy potential of the gravimetric (quasi)geoid models in the order of 3 – 5 cm at continental scales and 1 – 2 cm over shorter distances up to a few 100 km, provided that high quality and resolution input data are available. This is a very significant improvement compared to the last published (quasi)geoid model EGG97, the key elements being improved terrestrial and satellite gravity field data from the CHAMP and GRACE missions (e.g., DENKER 2005b and 2005c).

In connection with the EGGP, a consistent marine gravity data set was derived (DENKER and ROLAND 2005, ROLAND 2005), the merging of ship and altimetric data was studied (ROLAND and DENKER 2005c), and contributions were made to the cross-validation of terrestrial and satellite gravity data (ROLAND and DENKER 2003 and 2005a). In addition, the collected terrestrial data sets were utilized for the computation of gravity gradients at satellite altitude with regard to the coming GOCE satellite mission (DENKER 2003A, MÜLLER et al. 2004b, WOLF et al. 2003, WOLF and DENKER 2005, WOLF 2007). Linked to the EGGP are also the activities within the EUVN-DA project, an initiative to collect a dense network of GPS and levelling control points in Europe (KENYERES et al. 2006 and 2007).

A corresponding geoid project was established for Antarctica within IAG Commission 2. The project "Antarctic Geoid (AntGP)" (CP2.4), chaired by M. SCHEINERT, TU Dresden, is aiming at the improvement of the terrestrial gravity coverage and geoid in Antarctica. Intensive activities took place in order to get access to already existing data sets as well as to link the AntGP goals to planned surveys, especially within the framework of the International Polar Year 2007/2008. A close relation was maintained to the project "Physical Geodesy" (chaired by M. SCHEINERT and A. CAPRA, Italy) within the SCAR GIANT program. Reports were given regularly to the IAG and on dedicated conferences (e.g. SCHEINERT 2005). A case study for regional geoid determination in Antarctica was presented for the region of the Prince Charles Mountains and Lambert Glacier, East Antarctica (SCHEINERT et al. 2007).

Since 2003, absolute gravity measurements were performed in Scandinavia at about 30 stations co-located with permanent GPS sites. The observations were carried out by four groups including IfE in Hannover (TIMMEN et al. 2005 and 2006, PETTERSEN et al. 2005a and 2005b). The aim of the project is to study glacial isostasy effects and to provide ground truth data for the GRACE satellite gravity mission (MÜLLER et al. 2003a, 2003c, 2004c, 2005a, 2005b, 2006a, 2007).

Several investigations were carried out with respect to the upcoming GOCE satellite gradiometer mission (see also other sections of the present report); the activities concern the GOCE processing algorithms (KOOP and MÜLLER 2004), error studies (e.g., WOLF 2007, WOLF and MÜLLER 2004, WOLF 2006), calibration and validation topics (BOUMAN et al. 2005, DENKER et al. 2003c and 2003d, MÜLLER et al. 2003b and 2006b, TOTH et al. 2005, WOLF 2004), temporal variations in the GOCE data (JARECKI et al. 2005), quality assessment procedures (JARECKI et al. 2006), and a regional combination and validation experiment in Germany with heterogeneous data (LUX et al. 2006, VOIGT et al. 2006).

In a joint effort, the Bundesamt für Kartographie und Geodäsie (BKG), Frankfurt am Main, and IfE, Hannover, developed a new model for the height reference surface (quasigeoid) in Germany, which now serves as a standard for the conversion between GPS ellipsoidal heights and normal heights. BKG and IfE did independent computations based on two different methods, both relying on the remove-restore technique. The input data were point gravity observations with a spacing of a few km, a digital terrain model with a block size of 50 m, a global geopotential model as well as GPS and levelling control points. Due to insignificant differences between the two independent solutions, both results were simply averaged, yielding the final GCG05 model. The evaluation of this model with independent GPS and levelling points suggests an accuracy of about 1 to 2 cm. For details see DENKER et al. (2003B), IHDE et al. (2006a and 2006b), LIEBSCH et al. (2006), SCHIRMER ET AL. (2006), and IHDE et al. (2007).

Moreover, German scientists contributed to geoid studies in Iran (ARDALAN and GRAFAREND 2004) and Turkey (ÜSTÜN et al. 2005, EROL et al. 2007a and 2007b). Finally, the previous national report on regional and local gravity field modelling activities can be found in DENKER (2003b).

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Temporal Gravity Field Variations

F. FLECHTNER[1], T. GRUBER[2], R. SCHMIDT[1]

Introduction

At the end of the last century temporal variations of the Earth gravity field could only be derived for the very long wavelengths up to degree and order 2 and for some low degree zonal coefficients on an approximately weekly basis primarily by analysis of Lageos Satellite Laser Ranging (SLR) data. Since the launch of the German CHAMP (Challenging Mini-Satellite Payload for Geophysical Research and Application) satellite mission in July 2000 also high-low satellite-to-satellite tracking (SST) data have been exploited to monitor annual and semi-annual gravity variations on smaller spatial scales down to about 5000 km. The US-German Gravity Recovery and Climate Experiment (GRACE), launched in March 2002 and performing low-low SST observations with micrometer level accuracy, revolutionized our knowledge of the Earth gravity field. Today, not only the static gravity field can be determined with unprecedented accuracy but, for the first time, temporal variations at shorter wavelengths up to approximately degree and order 35 to 40 are traceable, thus allowing for the quantification of mass distribution and mass variations within the Earth system with monthly and even sub-monthly (e.g. 10-days) temporal resolution. Based on currently about 5-years worth of GRACE mission data a new era for basic studies on quantities of the Earth system such as the continental hydrological cycle, the ice mass balance in Greenland and Antarctica, the steric and mass-related contribution to sea level rise or the inter-annual ocean mass variation has been opened. This also led to the implementation of a special priority program "Mass transport and mass distribution in the Earth system" (ILK et al., 2004, 2005) by the German Research Foundation.

Temporal Gravity Variations from SLR, GPS and CHAMP

KÖNIG et al. (2005) estimated dynamic orbits and Earth system parameters from a combined GPS (ground data) and LEO data analysis. It could be shown that especially the accuracy of reference frame and low degree gravity field parameters benefits from such integrated analysis when compared to solutions where the GPS ground data and the LEO data is exploited in consecutive, but separate data analysis steps. These investigations were motivated by the work of ZHU et al. (2004) where the potential advantages of an integrated adjustment of CHAMP, GRACE and GPS ground data for the estimation of orbit, ground station and static and time variable gravity field parameters were demonstrated for the first time.

A first insight into the annual and semi-annual variability of the gravity field on spatial scales of some thousand km was gained from the analysis of CHAMP data based on the dynamic orbit determination method as described in REIGBER et al. (2003a) and REIGBER et al. (2005). SNEEUW et al. (2003 and 2005) analysed the time-variability of CHAMP-derived spherical harmonic coefficients using kinematic orbits and the energy balance approach.

Tidal and Non-tidal Atmospheric and Oceanic Short-Term Mass Variations

Short- and long-term gravity field variations due to half-daily, daily and long-periodic atmospheric and oceanic tides as well as non-tidal atmospheric and oceanic mass variations on hourly and daily scales have to be taken into account in the gravity recovery based on modern satellite gravity data from CHAMP, GRACE and GOCE. For CHAMP and GRACE such gravity variations are typically reduced during the orbit integration as a priori information to "de-alias" the corresponding monthly and long-term static gravity field results (FLECHTNER, 2003). In the case of GOCE gradiometer data the atmospheric and oceanic signal is directly corrected at the level gradiometer measurements to de-alias such signals in the GOCE-based estimates of the static field (GRUBER and PETERS, 2003). WIEHL and DIETRICH (2005) investigated the influence of the orbital sampling and the instrument parameterization of CHAMP and GRACE on the derived time-variable gravity field signals.

In this context, BIANCALE and BODE (2006) developed mean annual and seasonal atmospheric tide models based on 3-hourly and 6-hourly ECMWF surface pressure data, thus extending the limited set of available atmospheric tide models. In order to study the impact of uncertainties in ocean tidal models, one known source of spurious gravity signals in GRACE-only gravity models ("striping"), in WÜNSCH et al. (2005) a simulation study was carried out, using the difference of two ocean tide models as a proxy of such model errors. FLECHTNER et al. (2006) described the operational GRACE Level-1B atmosphere and ocean de-aliasing product (AOD1B) which is based on 6-hourly operational ECMWF meteorological data and a barotropic or a baroclinic ocean model. AOD1B is used to de-alias short-term non-tidal mass variations in the monthly GRACE

[1] Frank Flechtner / Roland Schmidt: GeoForschungsZentrum Potsdam (GFZ), c/o DLR, D-82234 Wessling, Germany, Tel. +49 - 8153 - 28-1735, Fax +49 - 8153 - 288-1297, e-mail flechtne@gfz-potsdam.de / rschmidt@gfz-potsdam.de

[2] Thomas Gruber: Institut für Astronomische und Physikalische Geodäsie, Technische Universität München, Arcisstraße 21, D-82290 München, Germany, Tel. +49 - 89 - 289-23192, Fax +49-89-289-23178, e-mail Thomas.Gruber@bv.tu-muenchen.de

gravity field solutions. The methodology to correct the atmospheric non-tidal mass variations was revisited by PETERS (2007). Non-tidal oceanic mass variations of the latest releases of AOD1B are derived from output of the baroclinic ocean model OMCT (Ocean Model for Circulation and Tides) of the Technical University of Dresden which is based on meteorological ocean surface forcing and precipitation and evaporation data. DOBSLAW and THOMAS (2006) showed that the impact of river run-off on global ocean mass redistribution (un-modelled in OMCT) can be neglected.

Monitoring the Continental Hydrological Cycle

Since during the processing of the GRACE mission data to monthly gravity field solutions known tidal as well as all short-term atmospheric and oceanic mass variations are taken into account, time-variable gravity signals derived from time series of GRACE-only gravity models mainly reflect mass redistribution at the Earth's surface due the continental hydrological cycle. This was verified in studies on global scales (RAMILLIEN et al., 2005a, 2005b; Schmidt et al., 2006a, 2006b; GÜNTNER et al., 2007) as well as on regional scales such as the monitoring of time variations of regional evapotranspiration rates (RAMILLIEN et al., 2006). In this way, GRACE-derived changes in surface mass anomalies can be expected to contribute to the quantification of the total water budget, which is an obviously underestimated quantity as indicated by the GRACE-derived amplitudes of annual and semi-annual signals being larger than predicted by global hydrological models. More recently RAMILLIEN et al. (2007) have analysed seasonal but also interannual change in land water storage over 27 large river basins from GRACE data and found significant negative trends for some of the largest basins indicating water mass loss over the investigated time period. NEUMAYER et al. (2006) showed a high correlation when combining temporal gravity variations resulting from superconducting gravimeter recordings, GRACE monthly gravity field solutions and global hydrology.

To extract hydrological (and other geophysical) mass variability from monthly GRACE gravity field solutions special smoothing techniques have to be applied to the non-physical meridional-oriented striping in the GRACE geoids and to avoid leakage from neighbouring basins or from the ocean. To this end, MARTINEC et al. (2007) performed a statistical analysis of the temporal variability of the GRACE Stokes potential coefficients and Schmidt et al. (2007) made an accuracy assessment for GRACE derived time variable gravity field solutions. KUSCHE (2007) suggested an approximate decorrelation and non-iso-tropic smoothing of time-variable GRACE-type gravity field models. HORWATH and DIETRICH (2006) estimated errors of regional mass variations inferred from monthly GRACE gravity field solutions. As an alternative to the concept based on spherical harmonics FENGLER et al. (2005, 2007) and SCHMIDT et al. (2006) calculated regional high-resolution temporal GRACE gravity models using spherical wavelets. SNEEUW et al. (2003) investigated the space-wise, time-wise, torus and Rosborough representation in gravity modelling. In SASGEN et al. (2007) a method based on Wiener filtering applied for an optimized estimation of secular trends over Antarctica.

GRACE Oceanic Applications

It has been shown by various authors that GRACE gravity field time series also trace mass-induced gravity variations over the oceans. For example, KANZOW et al. (2005) have intercompared global patterns of ocean mass signals based on early GRACE-only gravity field series provided by GFZ and CSR with in-situ ocean bottom pressure data from a ground truth site in the tropical northwest Atlantic Ocean and the ECCO ocean model. The study indicated a general agreement between these independent data sources but also showed remaining deficiencies in the GRACE data processing and suggested, among others, the substitution of the non-tidal barotropic ocean model by a baroclinic one. On a regional scale FENOGLIO-MARC et al. (2006) calculated mass variations in the Mediterranean Sea from analysis of hydrology corrected GRACE data and found reasonable agreement with altimetry-based estimates corrected for the steric part. LOMBARD et al. (2006) estimated steric sea level variations from a combined GRACE and Jason data analysis and found an overall good agreement. The net effect of the land water contribution to sea level change was estimated to be 0.19 ± 0.06 mm/yr which is comparable to the ice sheet contribution. VINOGRADOVA et al. (2007) investigated the relation between sea level and ocean bottom pressure and the vertical dependence of oceanic variability.

Post Glacial Rebound and Ice Mass Loss

Since 2003, absolute gravity measurements have been performed regularly by the Institute für Erdmessung Hannover in the Fennoscandian land uplift network covering Norway, Sweden, Finland and Denmark (TIMMEN et al. 2005, 2006). In cooperation with the national agencies and research institutions of the Nordic countries and BKG in Frankfurt, terrestrial absolute gravimetry is applied to observe the postglacial land uplift due to the isostatic adjustment of the crust. Nearly all absolute stations are co-located with continuously observing GPS stations. From the comparisons between the participating instruments, an overall accuracy of ±30 nm/s^2 is indicated for a single absolute gravimeter and a single station determination. Thus, the gravity change due to the land uplift may be observed with an accuracy of ±10 to 20 nm/s^2 for a 5-year period. One purpose of these terrestrial in-situ observations is to validate the GRACE results (ground-truth) and first promising results have been presented in MÜLLER et al. (2003, 2005, 2007a, 2007b). In the same context, WIEHL et al. (2006) showed how the Baltic Sea water mass variations mask the postglacial rebound signal in CHAMP and GRACE gravity field solutions.

Predicted changes in the geoid about Greenland to be used for GRACE validation have been described by FLEMING et al. (2005). SASGEN et al. (2005) described signatures of glacial changes in Antarctica, namely rates of geoid height change and radial displacement due to present and past ice mass variations. These are more or less due to changing ice mass balance and ice dynamics and shall be detectable by modern gravity space missions (FLURY, 2005). In SASGEN et al. (2007) secular trends in the geoid over Antarctica from the most recent GRACE gravity time series and geophysical models are evaluated and optimally combined by means of Wiener filtering. The results there indicate the improved quality but also homogeneity of the augmented GRACE gravity field series provided by different centres (including GFZ).

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Satellite Gravity Theory

N. SNEEUW[1]

Introduction

The four years since the last IUGG General Assembly in Sapporo have seen tremendous developments in spaceborne gravimetry. The sections on *Gravity Field Satellite Missions* and on *Temporal Gravity Field Variations* describe the exciting science that results from analysis of CHAMP and GRACE data. At the same time, these satellite missions, including GOCE, have accelerated the development of new methodological approaches. The sheer amount of data and unknowns to be inverted has stimulated the advancement of data handling strategies in several ways: both for functional and for stochastic modelling, both in brute-force numerical and in semi-analytical schemes, in validation techniques, a posteriori testing, and so on.

Some of the trends and developments in Satellite Gravity Field Theory that were identified by SNEEUW and KUSCHE (2007):

The observables from CHAMP, GRACE and GOCE are increasingly modelled as *in situ* observables in the theoretical framework of classical physical geodesy. Combined with semi-analytical approaches highly efficient algorithms have been developed.

Multiresolution, space-localizing representations have found their way from the mathematical realm into the geodetic mainstream. Although spherical harmonic parameterization remains the default approach for the current missions, more and more researchers exploit the benefits of spatio-temporal localization by multiresolution modelling.

Despite the great successes of GRACE in monitoring the time-variable gravity field, the Achilles' heel of such mission scenarios becomes obvious: separation of the gravitational observable into its constituent mass sources. To disentangle these individual sources, fundamentally lumped into the gravitational observable, requires high-quality a priori models for so-called de-aliasing purposes and a delicate characterization in space, time and spectral domains. The separability issue will only be aggravated in future missions of the same design with improved hardware, e.g., a GRACE-type mission with a laser interferometry link.

An improved understanding of the gravitational sensors on GRACE and GOCE has motivated and necessitated more advanced stochastic modelling.

Theoretical and computational aspects in the downward continuation and regularization of spaceborne gravimetric data, decorrelation and outlier detection in coloured-noise observations, full-covariance modelling, and the general design of 'smart' algorithms to tackle these issues more efficient than in the past, will continue to play a major role.

Geoscientific interpretation and application of CHAMP, GRACE and in the near future GOCE gravity field models requires a deeper understanding of the underlying noise characteristics and error propagation mechanisms inherent to these products. The combination with a priori models and data from complementary observing systems like satellite altimetry, GPS and INSAR requires a careful analysis of the information content and the resolving power of the various data sets.

Advances in gravity analysis techniques: *in situ* modelling

In the pre-CHAMP era, conventional gravity field modelling from satellite observations was rooted in dynamic satellite geodesy and orbit perturbation theory. It involved large-scale computations, extensive software packages and, at an institutional level, a certain critical mass of people and resources. As a result, only a few global players were involved in global gravity field modelling from satellites. The observables from CHAMP, GRACE and GOCE, in contrast, can be modelled as *in situ* observables in the theoretical framework of classical physical geodesy. This enabled smaller, mostly university-based, groups to get involved in global (but also regional) gravity field modelling from satellite-borne gravimetry, and to produce competitive gravity models.

A point in case is the *energy balance approach* or *Jacobi integral approach*, e.g. GERLACH et al. (2003a, 2003b) or VISSER et al. (2003) which came to fruition at the IAPG at TU Munich. In this approach the GPS-derived orbit positions and velocities are converted to *in situ* disturbing potential along the orbit. By careful reduction of accelerometer outputs and of auxiliary forces this method provided high-quality CHAMP-only gravity fields, cf. GERLACH et al. (2003c). Despite its quality the CHAMP-only gravity field quality proved insufficient to reveal long wavelength time variations that remained hidden in the observation noise and ground-track variability, cf. SNEEUW et al. (2003).

Similarly, the ITG at University of Bonn developed the Hammerstein-Schneider approach further to a level of sophistication that allows CHAMP and GRACE data processing with a competitive quality. This approach is characterized by short arcs (ILK et al., 2005), combined with

[1] Nico Sneeuw: Geodätisches Institut, Universität Stuttgart, Geschwister-Scholl-Str. 24D, D - 70174 Stuttgart, Germany, Tel. +49 - 711 - 685-83390 , Fax +49 - 711 - 685-83285, e-mail sneeuw@gis.uni-stuttgart.de

a boundary value formulation of the equations of motion. The theoretical background on integrals of motion as well as on the use of short-arc boundary value approaches has recently been further developed by SCHNEIDER (2004, 2005, 2006), SCHNEIDER and CUI (2005) and LÖCHER and ILK (2005).

A third *in situ* methodology is the kinematic approach in which GPS-derived orbit ephemeris is numerically differenced twice to provide 3D forces. Though elementary in principle, this approach also requires delicate data handling and corrections for nuisance force models. It was successfully implemented at the GIS, Stuttgart University, cf. REUBELT et al. (2003) or REUBELT et al. (2006).

GRACE's very high KBR accuracy demands orbit accuracy at a compatible level, which is hardly feasible considering GPS positioning. Thus, also for GRACE it seems to make sense to consider the KBR as *in situ* gravity field observable with GPS only providing the geolocation. SHARIFI and KELLER (2005) and SHARIFI (2006) convert the GRACE observable into a in-line along-track gravity gradient. See also NOVÁK et al. (2006).

Combined with semi-analytical techniques, leading to block-diagonal normal equation structures, gravity field recovery from *in situ* data becomes a highly efficient and fast recovery tool. Despite the necessary approximations, such a tool is used for CHAMP, GRACE and GOCE processing, e.g. WERMUTH and FÖLDVARY (2003) FÖLDVARY and WERMUTH (2005), often as quick-look tool, cf. WERMUTH et al. (2006).

Further advances

The sensors of such complicated systems as CHAMP, GRACE and GOCE require deeper knowledge of the appropriate stochastic models and associated estimation techniques. Several contributions have been made in the wider area of stochastic modelling, e.g. MARINKOVIC et al. (2003). ALKHATIB and SCHUH (2007) apply Monte Carlo covariance estimation to GOCE gravity recovery. Also robust estimation techniques and outlier detection methods have been thoroughly investigated to this end, e.g. KARGOLL (2005) or GÖTZELMANN et al. (2006).

When modelled in a straight-forward fashion, the huge numbers of observations and of unknowns lead to large equation systems that can only be dealt with by high-performance computing, also referred to as *brute force*. Much of this work was pioneered by ITG at University Bonn. More recent developments include improved stochastic modelling ALKHATIB and SCHUH (2007). At GIS, University Stuttgart, the LSQR method was topic of research. It could be established as a viable alternative to conjugate gradient and other methods, e.g. BAUR and GRAFAREND (2006), BAUR and KUSCHE (2007).

Specific issues that arise in high performance computation are treated by AUSTEN et al. (2006).

The methodology to calibrate space gravimeters and to validate the results of gravity field satellite mission has also been further advanced. In particular, the validation of GOCE observations by various techniques, e.g. cross-over analysis or upward continuation of terrestrial data, has been topic of research at IfE, University Hannover, e.g. JARECKI and MÜLLER (2003).

Great advances have been made in the area of multi-resolution gravity field modelling, much of which is due to the activities at University of Kaiserslautern, e.g. (FREEDEN and MICHEL, 2004). At the same time, in the past few years multi-resolution analysis has made the transition from mathematical research to a mainstream geodetic analysis technique for spaceborne gravity recovery, e.g. FENGLER et al. (2004), FREEDEN and SCHREINER (2005), FENGLER et al. (2007), or SCHMIDT et al. (2005, 2007).

Working group on Satellite Gravity Theory

Under the new IAG structure a joint working group on *Satellite Gravity Theory* was initiated between Commission 2 and the Intercommission Committee on Theory right after the IUGG general assembly 2003, Sapporo. According to its terms of reference the working group was dedicated to monitoring and stimulating research in gravity field estimation from satellite missions, merging, modelling time-variable gravity field representation and satellite orbit dynamics. Chaired by N. SNEEUW (Calgary, Stuttgart) this international working group had a strong German participation: MAYER-GÜRR (Bonn), KUSCHE (Delft, Potsdam), GERLACH, PETERS (Munich), NOVÁK (Stuttgart, Prague), WILD (Karlsruhe).

One of the working group's achievements, in collaboration with the IAG working group on *Inverse Modelling* (chair: J. KUSCHE), was a special issue of the Journal of Geodesy Vol. 81, Nr. 1, 2007, dedicated to the combined field of satellite gravity theory and inverse theory. Significant participation from German scientists documented the activities in these areas. In FENGLER et al. (2007) spherical wavelets as developed by the University of Kaiserslautern group have been established as a tool for multiscale modelling of the GRACE monthly gravity fields. In the same vein, the contribution by SCHMIDT et al. (2007) systematically reviews spherical wavelets with application to regional analysis and interpretation of CHAMP and GRACE gravity data. In the same issue ALKHATIB and SCHUH (2007) deal with the Monte Carlo covariance estimation and error propagation strategy. The authors focus on the recovery of the Earth's gravity field in spherical harmonics from the GOCE mission, a challenging and numerically huge task.

Activities in preparation of future missions

Despite the scientific successes and research activities around the satellite missions CHAMP, GRACE and GOCE, many groups have started to plan ahead. Most notably, IAPG at Technical University Munich group has initiated and organized several workshops and projects to this end. The full spectrum of spaceborne gravimetry—from orbit dynamics through geoscience applications to future concepts – is covered in the proceedings of one such workshop BEUTLER et al. (2003). A study on Future Satellite Gravimetry and Earth Dynamics, sponsored by the European Space Agency (ESA), culminated in a book edited by FLURY and RUMMEL (2005) of the same name. In it, the study participants lay out the requirements from various Earth science disciplines on future gravity field satellite missions. A number of mission scenarios are simulated to investigate whether future missions can meet such requirements SNEEUW et al. (2005).

More recently (April 2007) IAPG organized, together with SRON (Netherlands) and ESA, a dedicated workshop on the Future of Satellite Gravimetry. The workshop identified two main theoretical challenges for future gravity missions: 1) aliasing of fast time variations into the gravity solutions, and 2) separability of individual mass sources. Potential future measurement concepts, like atomic interference and optical clocks, were presented. Moreover the workshop participants, both from Europe and USA, engaged in more political and strategic discussions as to the organization and realization of future gravity missions.

Formation flying may help in solving some of the limitations of current gravity field missions. The feasibility and utility of formation flight for future dedicated missions was investigated by SNEEUW and SCHAUB (2005). From a more practical viewpoint GERLACH and VISSER (2006) investigated the potential geodetic use of the geomagnetics mission SWARM. Unless a dedicated mission is funded for the post-GRACE and -GOCE era, the SWARM constellation of three satellites, all carrying GNSS-receivers, may be one of the few sources of satellite gravimetry in the years to come.

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COMMISSION 3

EARTH ROTATION AND GEODYNAMICS

Overview and Highlights

J. MÜLLER[1]

Introduction

The determination of Earth rotation is one of the main tasks of geodesy. Variations of Earth rotation due to the redistribution of masses within the Earth system are closely related to the deformation of the geometric shape of the Earth and the temporal variations of its gravity field.

The report on the activities of German scientists in Earth rotation and geodynamics research during the period 2003 to 2007 is subdivided in the following sections:

- Crustal deformation and Geodynamics,
- Earth Tides and Non-tidal Gravity Field Variations,
- Geophysical Fluids,
- Earth Rotation – Theory and Analysis,
- Sea Level and Ice Sheets,
- International Earth Rotation and Reference Systems Service (IERS).

German scientists contributed in various ways to the objectives of IAG commission 3, which is described in the above mentioned sections. Here, only a few examples for intensive research activities are given.

In Germany, geodesy has a long-standing tradition in research and education. It serves as a bridging discipline within the geosciences and has often been the driving factor in organising larger research projects. This also holds for *Earth Rotation* and *Geodynamics.*

Earth Rotation

The rotation of the Earth does not only relate the terrestrial and the quasi-inertial reference systems to each other; moreover, its variations contain essential features of global dynamic processes. Correspondingly, Earth rotation research is multi-disciplinary with a close interrelation between modelling, observation, and analysis. The Earth has to be considered as a complex system of interacting dynamic components. The variations of Earth rotation are global and integral indicators of ongoing changes in the dynamics of the Earth, both for the redistribution of masses inside and outside the Earth and for mass motions like wind and oceans currents (see SCHUH et al. 2003).

The German Earth rotation community succeeded in 2006 to allocate funds for a so-called research unit "Earth rotation and global dynamic processes" of the DFG (Deutsche Forschungsgemeinschaft – German Research Foundation). The main objective of this coordinated research unit is to describe and explain the physical phenomena which contribute to variations of Earth rotation. Interactions and couplings of the various sub-systems are taken into account and dedicated analyses of the dynamic processes are carried out.

The research unit is coordinated by J. MÜLLER (also chairman), H. KUTTERER, both University of Hannover and M. SOFFEL, Technical University of Dresden. It is composed by scientists and institutions from geodesy, geophysics, meteorology and oceanography. The unit is organized in ten thematic projects which are

- Earth rotation and information system: Development of a virtual Earth rotation system for geodetic and geoscience applications (ERIS),
- Earth rotation and ocean circulation,
- Consistent post-Newtonian nutation series of a 'rigid' Earth model,
- Mass motions in the Earth's core and mantle and their influence on polar motion and the gravity field,
- Lunar Laser ranging: Consistent modeling for geodetic and scientific applications,
- Integration of Earth rotation, gravity field and geometry using space geodetic observations,
- Modelling of episodic-transient signals in measurements of large ring lasers,
- Investigation of sub-daily and episodic variations of Earth rotation,
- Usability of time-variable Earth orientation parameters and gravity field coefficients from satellite missions for mutual validation and combined analysis,
- Long-term ERP time series as indicator for global climate variability and climate change.

More information on the DFG Research Unit FOR584 can be obtained from *http://www.erdrotation.de*.

In a second research initiative, an earth system model for the simulation of variations of earth rotation, deformation and gravity field, which are induced by atmospheric, oceanic and hydrological processes and their interaction, has been developed (see THOMAS et al., in this report).

Geodynamics

A further joint research project, mainly motivated by the successful performance of GRACE and its overwhelming input for Earth system research was prepared by ILK et al. (2005), which resulted in a so-called DFG priority programme "Mass transport and mass distributions in the system

[1] Jürgen Müller: Leibniz Universität Hannover (University of Hannover), Institut für Erdmessung (Institute of Geodesy), Schneiderberg 50, D - 30167 Hannover, Germany, Tel. +49 - 511 - 762-3362, e-mail mueller@ife.uni-hannover.de

Earth" in 2006. This programme which is coordinated by KH. ILK will run for six years – the first initial projects have been funded for two years.

Mass transport shows up on various spatio-temporal scales and includes any changes in the sub-systems of the Earth. The ocean circulation, changes of ground water level and solid Earth moisture, melting of continental ice sheets, river run off, changes of sea level and convective flow in the Earth mantle, all these effects cause transport and re-distribution of masses.

Using innovative and extremely precise sensor systems, dedicated gravity field and altimeter satellites observe the implication of these processes. The common analysis of this data shall improve the knowledge about these processes within the system Earth.

The themes (i.e. the main research topics of the first phase), which again comprise a number of projects, are

- Observing the Earth system from space,
- Ocean dynamics,
- Ice mass balance and sea level,
- Glacial isostatic adjustment,
- Dynamic of crust and mantle,
- Continental hydrology,
- Consistent data combination and mass signal separation.

More information on the DFG Priority Programme SP1257 can be obtained from *http://www.massentransporte.de*.

The geodetic research in polar regions, which has been intensified recently due to the International Polar Year 2007/2008, or the investigation of sea level changes benefit largely from those coordinated activities (see also the chapter of DIETRICH in this report).

These joint research programmes also provide significant contributions to international activities such as the project GGOS (Global Geodetic Observing System) which has been established and coordinated by the International Association of Geodesy (IAG), see the separate section of M. ROTHACHER on GGOS in this report. The consistent modelling/analysis as well as the combination and integration of the various observation methods therefore present important efforts to global geodesy.

Related activities

German scientists contribute to almost all IAG bodies, e.g. H. DREWES (DGFI) as president of IAG-Commission 1, which has direct or indirect effect on the other Commissions, too. Here, only a few activities related to the IAG Services are mentioned. Since 2001, the IERS Central Bureau is hosted and funded by the Bundesamt für Kartographie and Geodäsie (BKG). Its tasks in the past years are documented in a separate section by B. Richter below. German geodesists also take leading positions in further IAG Services such as A. NOTHNAGEL (IVS), J. MÜLLER (ILRS), M. ROTHACHER (IERS, GGOS), or J. DOW (IGS) whose work guarantee international integration. Their activities are described within the sections addressing the respective topics.

Finally also the very large support of Germany on the observational side should be mentioned: At the fundamental station Wettzell (and similar TIGO in Concepcion, Chile), not only all space geodetic techniques are operating (see section by A. NOTHNAGEL), but they also contribute significantly to the determination of all Earth orientation parameters as well as the realisation of the international celestial and terrestrial reference systems.

The contribution of Germany to design, realise and operate the gravity field satellite missions CHAMP, GRACE and GOCE as well as their analyses is addressed in the section by F. FLECHTNER and T. GRUBER.

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Crustal deformation and Geodynamics

H. DREWES[1], D. WOLF[2]

Introduction

German investigations on geodetic research of crustal deformation and geodynamics include geometric and gravimetric observation campaigns, data processing and modelling, analysis and interpretation of results, and theoretical studies. The report for the period 2003-2007 shall be divided into the topics

- Global tectonic deformations (including plate kinematics and dynamics);
- Glacial-isostatic adjustment (including mantle viscosity);
- Regional (primarily vertical) deformations (in Germany, Europe and other regions);
- Theoretical studies and viscoelastic field theory.

Global tectonic deformations

Tectonic deformations on a global scale are closely connected with plate tectonics. The kinematics of lithospheric plates is observed by networks of the different space geodetic techniques (GPS, SLR, VLBI, DORIS), where German institutions are strongly involved with fundamental observatories co-locating various techniques (Wettzell/ Germany and Concepción/Chile operated by Bundesamt für Kartographie und Geodäsie, BKG, and Potsdam/ Germany operated by GeoForschungsZentrum Potsdam, GFZ) and other permanent stations, mainly GPS. Actual plate kinematic and deformation models are frequently computed from the global observations by Deutsches Geodätisches Forschungsinstitut (DGFI, DREWES and MEISEL, 2003). They include now the modelling of nearly all major plates (except Cocos) and the larger inter-plate deformation zones (orogenes in the Mediterranean, Himalaya, California, Andes) and provide point velocities with accuracies better than 1 mm/year. Plate dynamics was studied by TRUBITSYN et al. (2006).

The deformations between the rigid plates are geodetically measured in many regional networks, mainly by GPS observations. They include also specific projects for earthquake research. Since many years there have been several German projects in the Andean subduction zone in South America. A large area in the southern and central Andes were investigated by KHAZARADZE and KLOTZ (2003) studying long-term and short-term effects related to earthquakes. BAEZ et al. (2007) presented results from the permanent Chilean network. Post-seismic mechanisms of the 2001 Peru earthquake were investigated by HERGERT and HEIDBACH (2006). The Cariaco earthquake in Venezuela was studied by BAUMBACH et al. (2003). In Europe projects concentrate on the Mid-Atlantic ridge. In a cooperation with the Icelandic Meteorological Office and the Nordic Volcanological Center of the Institute of Earth Sciences (Reykjavik), the Bayerische Kommission für die Internationale Erdmessung (BEK) participated in the processing of GPS data from the ISGPS network in Iceland (GEIRSSON et al., 2006). The strongest signal observed is due to plate spreading across Iceland. The plate boundary deformation field was affected in South Iceland by two M_w = 6.5 earthquakes in June 2000, inflation at Kafla volcano during 2000 and 2004, and an eruption of Hekla volcano in February 2000. KANIUTH (2005) studied the displacements after the strong Sumatra 2004 and 2005 earthquakes.

A project for observing continental deformation in the Alps was funded by the EU INTERREG III-B Programme. Several research and environmental institutions from France, Germany, Italy and Slovenia were involved. DGFI and BEK were partners in this project. During the last three years more than 30 permanent GPS stations were installed in the alpine region.

General studies of mechanisms and geodetically observable effects (gravity and position changes) were published for convergent zones (Central America, KRAWINKEL 2003) and spreading zones (JACOBY and CAVSAK, 2005).

Glacial-isostatic adjustment

Geographically, most studies of glacial-isostatic adjustment (GIA) and its relation to mantle viscosity were concerned with Fennoscandia. As a measure of GIA, present-day temporal variations of gravity may be used. Using observations since 1966 along a profile crossing Fennoscandia near 63° N, MÄKINEN et al. (2004, 2005) derived ratios between gravity change and uplift of -0.16 to -0.20 µgal/mm for this region. Recently, the relative measurements have been complemented and will eventually be replaced by new techniques. Thus, absolute gravity measurements have been intensified in Fennoscandia since 2003. Simultaneously, monthly solutions for the geoid derived from measurements of the GRACE satellite mission have become available and can be exploited to better constrain GIA in Fennoscandia and elsewhere. Further details about these new initiatives may be found in MÜLLER et al. (2003, 2005, 2006), and

[1] Hermann Drewes: Deutsches Geodätisches Forschungsinstitut (DGFI), Alfons-Goppel-Str. 11, D - 80539 München, Germany, Tel. +49 - 89 - 23031-1106, Fax +49 - 89 - 23031 1240, e-mail drewes@dgfi.badw.de

[2] Detlef Wolf, GeoForschungsZentrum Potsdam (FZ), Dept. 1, Telegrafenberg, D - 14473 Potsdam, Germany, Tel. +49 - 331 - 288-1140, Fax +49 - 331 - 288-1163, e-mail dasca@gfz-potsdam.de

TIMMEN et al. (2006). GPS observations were evaluated and interpreted by KANIUTH and VETTER (2005).

On a longer time scale, the postglacial uplift of a region glaciated during the late Pleistocene can be inferred from uplifted Holocene shorelines. Combining this evidence with present-day uplift rates inferred from the BIFROST GPS stations in Fennoscandia, STEFFEN and KAUFMANN (2005) inferred improved values of the mantle viscosity for this region. A standard technique is the conversion of the quasi-exponential postglacial uplift into a relaxation-time spectrum and its inversion in terms of the mantle viscosity. This method was used in three studies of GIA in Fennoscandia. In the first, FLEMING et al. (2003) investigated to which extent estimates of lithosphere thickness and upper-mantle viscosity are modified if the conventional assumption of an elastic lithosphere is replaced by the more realistic assumption of a viscoelastic lithosphere. In the second study, KLEMANN and WOLF (2005) investigated how estimates of the relaxation-time spectrum are modified if meltwater-induced sea-level changes accompanying the Holocene uplift are considered. Finally, MARTINEC and WOLF (2005) interpreted the Fennoscandian relaxation-time spectrum in terms of an axisymmetric viscosity distribution, resulting in a lithosphere thickness of about 200 km in the central region and a lithosphere thickness of about 80 km in the periphery. The inversion was based on the spectral finite-element method recently developed by Martinec for a self-gravitating spherical earth model with a 3-D viscosity distribution. An alternative technique available for 3-D viscosity models is the standard finite-element method. This was used in two studies also concerned with GIA in Fennoscandia. In the first, STEFFEN et al. (2006) compared predictions of present-day uplift and horizontal motion based on 1-D viscosity models with those for a 3-D viscosity distribution derived from seismic shear-wave models. They demonstrated that differences of about 2 mm/a may result due to the neglect of the 3-D structure. In the second study, STEFFEN et al. (2007) investigated the sensitivity of the present-day uplift and horizontal motion with respect to the viscosity region considered. Their results indicate that the sensitivity of GIA is largest to the viscosity of the upper mantle below the former ice sheet.

A number of studies were concerned with Canada. WOLF et al. (2004, 2006) analysed GIA in the Churchill region, western Hudson Bay. Using Holocene shorelines, absolute gravimetry, GPS and tide-gauge measurements, they demonstrated that the observational evidence is mutually consistent and inferred improved values of the upper- and lower-mantle viscosities for this region. In another study, KLEMANN and WOLF (2007) considered the Holocene shoreline evidence for the Richmond Gulf region, eastern Hudson Bay, located near the uplift centre. Based on fuzzy-logic analysis, they derived an improved value of about 5 ka for the relaxation time of the exponential function best fitting the uplift curve inferred from the shorelines.

In several papers, GIA in other regions was studied. HAGEDOORN and WOLF (2003) investigated the late Pleistocene and present-day deglaciation of Svalbard. Using viscoelastic earth models and comparing predictions of the deglaciation-induced uplift and geoid rise with results based on GPS, VLBI and tide-gauge measurements, they suggested a regional sea-level rise of about 3 mm/a. KAUFMANN (2005) predicted the present-day changes in gravity and geoid resulting on the hypothesis of a extensive late Pleistocene ice-sheet in Tibet. They demonstrated that the peak signals produced by its melting are sufficiently large to be detected by the GRACE satellite mission. KAUFMANN et al. (2005) predicted the present-day uplift and horizontal motion for Antarctica using different scenarios of the late-Pleistocene de-glaciation as well as 1-D and 3-D viscosity models. Whereas the uplift strongly depends on the ice model chosen, the horizontal motion is more sensitive to the viscosity model selected. FLEMING et al. (2007) interpreted GIA near the Vatnajökull ice cap, Iceland. Considering three models of the ice-cap evolution between the year AD 900 and today, they compared predictions of the present-day uplift with values based on GPS campaigns conducted between 1991 and 1999. Their main result is that the details of the deglaciation history during the last one or two decades are significant for correct inferences of the mantle viscosity below Iceland. In a further study, KLEMANN et al. (2007) computed the present-day displacement rate caused by the response of the earth to the mass loss of the Patagonian ice field, South America. The complex tectonic structure near the Antarctic and South American plates was modelled using a 2-D viscosity model. The predicted rates demonstrate the sensitivity of the response to the particular features of the earth structure. SASGEN et al. (2007) studied the occurrence of Aeolian sediments on Berkner Island, Antarctica, retrieved from near the base of an ice core. Using the most realistic combination of viscosity model and Antarctic glacial history, they showed that sediment deposition was possible between 114.5 and 92.2 years ago. HAGEDOORN et al. (2007) investigated the influence of GIA caused by the late Pleistocene deglaciation on the present-day sea-level variations. Using regional viscosity and ice models optimised on the basis of the Holocene shoreline evidence and allowing for melt-water influx, ocean loading as well geoid and rotational effects, they predicted the GIA-induced contribution to the sea-level variations for a global distribution of tide-gauge stations. A reduction of the observational linear trends with respect to the GIA contribution resulted in a value of about 1.5 mm/a for the global mean sea-level rise.

Regional Deformations

Monitoring regional deformations in Germany focused on vertical crustal movements. A working group of the German Geodetic Commission (DGK) coordinates these activities. Regions of special interest are the tectonically active upper Rhine Graben (ROZSA et al., 2005), the Eifel Plume (SPATA et al., 2003), the sedimentary fillings in the lower Rhine embayment (GÖRRES et al., 2006), and the Vogtland earthquake area (WENDT and DIETRICH, 2003). Besides the interpretation of new and historical precise spirit levelling, repeated GPS observations are applied. RABUS and KNÖPFELE (2003) compiled maps of vertical movements from differential InSAR profiles. ZIMMERMANN (2004) studied the general concept and the realization of an information system for geodetic deformation analysis.

In Europe, there are detailed investigations on vertical crustal movements covering the whole continent and concentrating on specific regions, respectively. Long time series of continuous GPS observations, principally within the European Reference Frame (EUREF) provided by H. HABRICH, BKG, were used to study atmospheric loading effects and to derive local regression coefficients between the atmospheric pressure and vertical displacements (KANIUTH and HUBER, 2003, 2004; KANIUTH and VETTER, 2006). Ocean loading is a strong effect of vertical motions at coastal sites, which can be estimated from GPS observation data (KANIUTH and VETTER, 2005). RICHTER et al. (2004) combined space geodetic results (GPS and VLBI) with absolute gravimetric observations in Medicina, Italy, and found high correlations but also interesting discrepancies.

Investigations on regional crustal movements outside Europe concentrated primarily on South America. DREWES et al. (2005) compared the results of two continental GPS campaigns of the SIRGAS project 1995 and 2000 to derive 3D station displacements. These results entered into a continental deformation model derived by a combination of the finite-element method and a geodetic collocation approach (DREWES and HEIDBACH, 2005). The number of continuously observing GPS stations in South America has strongly increased during the last years (SEEMÜLLER and DREWES, 2004). Time series of weekly station coordinates and velocities from multi-year solutions were provided by SEEMÜLLER et al. (2004). Environmental effects and local displacements were studied by KANIUTH and STUBER (2005) in two GPS stations at the IGS site Bogotá, Colombia.

Theoretical studies

The application of satellite gravity missions for monitoring vertical crustal deformations due to hydrological mass loading requires the detailed investigation on the complex relations between the mass displacements and gravity variations. KUSCHE and SCHRAMA (2005) studied inversion by comparing time series of the GRACE gravity field with those of the global GPS network. RAMILLIEN et al. (2005) recovered the surface-water masses by the inversion of GRACE geoid models. Other authors (e.g., SCHMIDT et al. 2006) used these models for the representation of mass variations and subsequent vertical crustal movements by suitable mathematical functions.

In a theoretical study concerning glacial-isostatic adjustment, KLEMANN et al. (2003) deal with the appropriate consideration of compressibility in viscoelastic earth models. Deriving analytical solutions for the load-induced perturbations of a homogeneous half space, they showed that the solution to the problem involves several types of singularities. In addition, Rayleigh-Taylor instabilities resulting from internal buoyancy arise. These compressibility effects correspond to those recently analysed by Vermeersen and Hanyk for a homogeneous viscoelastic sphere. In a further theoretical study, MARTINEC (2007) derived the propagator matrix for the response of a multilayered viscoelastic sphere to surface toroidal traction in analytical form. The solution is suitable for testing the performance of numerical algorithms for computing GIA.

Statistical analyses of the components of the strain tensor in southern and western Europe derived from space geodetic observations were presented by CAI and GRAFAREND (2007a). They applied the method to studies of the strain in Fennoscandia. RIEDEL et al. (2007) developed an approach for the analysis of landslides from differential InSAR measurements.

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Earth Tides and Non-tidal Gravity Field Variations

B. RICHTER[1]

Instrumental investigations

The high performance of the 43 m long water-tube tiltmeter in the Underground Laboratory for Geodynamics in Walferdange (Luxembourg) lead to diurnal and semi-diurnal tidal measurements in excellent accordance with the models. The analysis of 7 years dataset show the lowest standard deviation among all results obtained with other tiltmeters in Walferdange, e.g. phase uncertainties for M_2 of less than 0.024° equal (3s). In addition for the first time tilt induced by the non-linear tides ($2MK_3$, M_3, MN_4, M_4 and MS_4) in the North Sea are observed clearly (D' OREYE and ZÜRN 2004a, 2004b, 2005, 2006).

The seismic free oscillations of the Earth (frequency band 0.3 to 20 mHz) as well as signals below 1 Mhz which are more sensitive to density distributions within the Earth open a window to study the Earth interior and structure. While in the majority of cases observations of spring gravimeters deployed in the international Deployment of Accelerometers (IDA) network and more recently on the Streckeisen STS-1 seismometers deployed in the global seismic network (GSN) are used the latest generation of Superconducting gravimeters (SG) opens an opportunity to complement the ensample especially on the seismic low frequency band. Noise investigations and comparisons between seismometers and gravimeters performed by the Black Forest Observatory are the indispensable basis to assess the strength of SG (WIDMER-SCHNIDRIG, 2003, ZÜRN and WIDMER-SCHNIDRIG, 2003).

Extensive analyses of data from superconducting gravimeters (SG) were carried out with regard to the noise content in the spectral range between Earth's free oscillations and the short-periodic tides. The objective was to obtain an estimate on the traceability of small geodynamic signals such as Slichter and other core modes and to identify remaining noise sources. It was found that despite sophisticated reductions the data still contain environment-related signals due to air pressure and hydrological variations. From analyses of records from dual sensor instruments it was found that the instrument-related noise level is about an order of magnitude below the typically obtained level. These studies also showed an instrument/sensor unit-dependent air pressure influence on the observations of superconducting gravimeters in the range of 1-3% of the total effect (KRONER et al. 2004, KRONER et al. 2005).

Tidal investigations

12 GGP stations (BE, BO, CA, CB, MB, MC, MO, PO, ST, SU, VI, WE) are analyzed to determine the elastic behavior of the Earth in the frequency domain of the Chandler wobble. The length of the data series used varies between 4 and 18 years. The annual wave and the Chandler wobble were separated by fitting two sinusoidal functions with periods of 365.25 and 432 days to the residual gravity. The δ-values of the Chandler wobble is close to 1.16. The corresponding values of the annual wave are slightly smaller but more noisy. The phase lags for both periods are in the order of a few degrees (HARNISCH and HARNISCH 2006b).

Non Tidal Effects

Deployment of time-dependent gravity observations for hydrological studies

South Eastern Po plain

For more than 10 years an Italian and German research team studies the natural and anthropogenic subsidence in the South Eastern Po Plain. The area is well suited to test the application of an observational strategy which combines different techniques to extract information on the spatial and temporal variability of the subsidence. Starting with permanent GPS and gravity observations at a few stations the experiment is complemented by episodic absolute gravity observations for validation of the individual time series.

The series of gravity recordings at the stations Medicina (Italy) are investigated to separate seasonal gravity variations from long-term trends in gravity. The findings are compared to height variations monitored by continues GPS observations. A clear seasonal signal is visible in the gravity and height data series, caused by fluctuations in the atmosphere including mass redistribution, the ocean, groundwater but also by geo-mechanical effects such as soil consolidation and thermal expansion of the structure supporting the GPS antenna (RICHTER et al. 2004, ROMAGNOLI et al. 2003). The combination of velocities derived from the GPS and gravity data, further complemented by the results of the InSAR Permanent Scatter technique allows us to monitor continuously in space and time vertical crustal movements. The combination takes advantage of the complementary strengths of each technique, by overcoming the limitations inherent in each single technique alone. Here, long-term trends were derived

[1] Bernd Richter: Bundesamt für Kartographie und Geodäsie / Federal Agency for Cartography and Geodesy (BKG), Referat G1 "Grundsatz und globale Referenzsysteme", Richard-Strauss-Allee 11, D-60598 Frankfurt a.M., Germany, Tel +49-69-6333-273, Fax +49-69-6314905-20, e-mail bernd.richter@bkg.bund.de

enabling us to map the behaviour of subsidence (even exceeding 20 mm/yr) with high spatial resolution in the South Eastern Po Plain. The uplifting behavior of the Apennines chain bordering the Po Plain is identified together with a narrow zone separating the contrasting vertical crustal movements (ZERBINI et al. 2007).

Wettzell

Performing comparable investigations at Wettzell (Germany), no seasonal effect could be clearly identified, and the long-term trend in gravity is mainly caused by ground water variations. To take full advantage of the high capabilities of the modern superconducting gravimeters (high sensitivity, low and stable drift-rate), hydrological data have to be incorporated in the gravimetric data processing, especially if long-term phenomena with small amplitude are studied (Harnisch and Harnisch 2006a). The successful combination of height and gravity series with the derived ratio of gravity to height changes indicates that the long-term trends in height and gravity are likely due to mass changes rather than to tectonic movements (RICHTER et al. 2004).

Moxa

The continuous observations with the superconducting gravimeter at Moxa as well as the repeated measurements with LCR-gravimeters are used to study the benefit of these data for hydrological studies. This research was supported by a number of hydrological experiments and modelling to study the influence of hydrological changes in certain areas on the SG observations (KRONER and Jahr 2006). Among other things the gravity effect of a water front moving downhill could be investigated. In the records of the superconducting gravimeter typically hydrological effects of up to several nm/s² are visible. With regard to time-dependent changes in the gravity differences obtained on the local network the following was found: Maximum effects occur between the observation site at the foot of the hill and the one on the upper hill flank (KRONER et al. 2007, NAUJOKS et al. 2006). With increasing distance of the observation point at the valley bottom the variations in the differences decrease. From the systematics found, which were confirmed by modelling, it could be shown that unexpectedly a significant amount of water needs to be stored in the joints of the hill flank in order to explain the changes in the gravity differences (KRONER 2006). The water volume stored as soil moisture and groundwater is not enough to produce the observed effects in gravity (KRAUSE et al. 2006). A subsequent consideration of this influence in the SG data led to a qualitatively good agreement between the observation at Moxa and a modelling of the gravity effect based on global hydrological models (NEUMEYER et al., 2006).

For the catchment area of Moxa observatory hydrological models were developed (HASAN et al., 2006; KRAUSE et al., 2005). Simultaneously a 3D gravity model for Moxa observatory, which takes into account the complex topography and geological situation, was derived from areal gravity measurements. Changes in the different compartments based on hydrological modelling are introduced into the gravity model as density changes and the resulting gravity variation for the different observation points is computed. By comparison of model-derived and observed gravity changes additional constraints for hydrological modelling ought to be obtained. The repeated gravity measurements have already helped to identify one hydrological contributor which was not known beforehand to have a major influence on gravity: changes in the water storage inside the fissured hill flank.

Time-dependent gravity observations at volcanoes

The studies at Mayon volcano – Philippines were continued by improved modelling of the gravity variations. Here, not only elastic deformation was taken into account but also the gravitational effect of the deformed edifice. With this model it was possible to explain the obtained gravity variations much better than with a deformation model alone. The algorithm was further developed for geodetic data in volcanic areas (VAJDA et al. 2004, TIAMPO et al. 2004a, 2004b, 2004c).

These micro-gravimetric studies were also applied to the volcanoes Merapi – Indonesia and Galeras – Colombia (JENTZSCH et al. 2004).

Verification of ocean tidal models

In order to synthesize the gravity value for points worldwide from the standard gravity formula and the ocean tide loading, a comprehensive comparison was performed using worldwide tidal gravity and tilt results. Three TOPEX/POSEIDON (T/P) satellite derived models (CSR3.0, FES95.2 and TPXO.2) beside the classical SCHW80 model were selected for an accuracy assessment study. The selected models have been subjected to an intercomparison test, tide gauge validation test and comparison to 59 tidal gravity stations. The intercomparison test shows a good agreement between the T/P-based models for the open ocean and remarkable disagreement between the selected models in the coastal regions indicating that such models are still problematic in these regions. The tide gauge validation shows that the T/P derived models fit tide gauges better than SCHW80, with a better fit for the semidiurnal constituents than for the diurnal constituents. Comparing the gravimetric ocean-tide loading computed from the selected models with the residuals from a set of 59 tidal gravity stations shows that there is an improvement of the T/P derived models with respect to the Schwiderski model, especially in M2. However, this improvement is not as significant as the result of the comparison with the pelagic data. A procedure developed for the comparison of T/P derived models with SCHW80 was developed. The results also provide information about the improvement of SCHW80, as well as about the properties of the new models. It is intended to continue this work applying the very recent models to see how they perform compared to this study (ZAHRAN et al. 2005, ZAHRAN et al. 2006).

The non-tidal ocean loading effect has been observed in the height series of four permanent GPS stations, namely Medicina, Marina di Ravenna, Bologna and Trieste, located in the northeastern Adriatic area. A validation of the ECCO model is performed in the Adriatic, a semi-enclosed basin in the Mediterranean Sea, by comparing model sea-surface elevation with tide-gauge and TOPEX/POSEIDON data, and model bottom pressure with that estimated from temperature and salinity observations. Using the ECCO model ocean bottom pressure data and the Green's functions approach, the non-tidal ocean loading effect has been modelled at the four GPS sites. The height series and the predicted non-tidal ocean loading are highly correlated at all four stations. A similar analysis is also presented for the superconducting gravimeter data collected at the Medicina station (ZERBINI et al. 2004).

In contrast to the long-term variations in the atmosphere the high frequency band excite seismometers and gravimeters in a different manner. Acceleration power spectral densities of vertical seismic noise at the best seismic stations show a minimum near 3 mHz. This minimum is caused by a cancellation near this frequency of Newtonian attraction vs. free air and inertial effects exerted by atmospheric phenomena on the sensor mass. Simplistic models of atmospheric phenomena are used to quantify this effect and examples are shown for special atmospheric events in ZÜRN and WIELANDT (2007).

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Geophysical Fluids

B. RICHTER[1], F. SEITZ[2]

Temporal variations of the Earth's rotation, its gravity field and its geometry are caused by a multitude of gravitational and geophysical processes within and between individual components of the Earth system. The largest effects are due to tidal deformations of the solid Earth and mass redistributions within the fluid components atmosphere and hydrosphere.

Several research programmes are proposed to the German Research Foundation in order to study the Earth's reaction on gravitational and geophysical excitations. The general aim of most of these investigations is the development of physically consistent models of the Earth system and its components for the simultaneous investigation of rotation, gravity field and geometry of the Earth in interdisciplinary cooperation (SCHUH et al. 2003).

Fluctuations of Earth rotation, gravity field and geometry are associated with the redistribution and motion of mass elements in the Earth system. In order to study the Earth's reaction on geophysical excitations, a dynamic Earth system model has been developed which is based on the balance of angular momentum in the Earth system (SEITZ 2004). During the last years efforts have been made in the development of a fully coupled atmosphere-hydrosphere model which provides the possibility to assess the combined effect of mass variations including tides on the basis of consistent exchange of mass, energy and momentum among atmosphere (ECHAM GCM), oceans (OMCT) and continental hydrosphere (HDM). It has been shown in several studies that model results for Earth rotation, solid Earth deformations and low-degree shperical harmonic coefficients of the Earth's gravity field from coupled models agree well with geodetic observations. However some investigations showed that the use of different numerical models and reanalysis data sets as forcing conditions for dynamic Earth system models influences the resulting parameters significantly (STUCK et al. 2004, THOMAS et al. 2004, SEITZ 2005). Some of the forcing conditions and model set-ups differ conceptually, e.g. with respect to the (back-)coupling of the atmosphere model the ocean model, the assumption of inverse or non-inverse barometric response of the ocean to atmospheric pressure variations and the inclusion of tides in oceanic circulation models.

The usability of ECMWF's forecasts for the determination of diurnal and semidiurnal mass variations in the atmosphere-ocean system due to atmospheric pressure tides has been examined and contrasted to corresponding variabilities deduced from ECMWF's analyses. While the diurnal pressure tide and the oceanic response simulated with a baroclinic ocean model are well resolved from both analyses and forecasts, the semidiurnal tide can be recovered from 3 hourly forecasts only. In terms of rms values of geoid height anomalies, forecast errors cause 0.18 mm, different wind representations 0.09 mm, and the doubled temporal resolution 0.20 mm of deviations between forecasts and analyses. Since atmospheric tides are highly variable, a time-invariant harmonic approach might not meet high precision requirements as for the GRACE mission and for high-resolution Earth rotation parameters. Considering these forecast errors, forecasts allow to account for atmospheric variability and corresponding oceanic responses down to semidiurnal timescales, dispensing with any additional model of atmospheric tides (DOBSLAW and THOMAS 2005).

In order to de-aliase and calibrate the gravity products available by the gravity missions refined geophysical fluid models are indispensable. Continental water mass redistributions, which are not covered by the coupled atmosphere-ocean model, shall be considered by an external hydrological discharge model in order to balance the global water cycle. Globally gridded precipitation-data sets are an essential base for various applications in the geosciences and for instance global and regional studies on the hydrological cycle or the evaluation of global circulation models (GCM's) (BECK et al. 2004). The impact of river run-off on global ocean mass redistribution is analysed by means of simulations with the baroclinic general circulation model OMCT driven by real-time atmospheric forcing fields from the European Centre for Medium Range Weather Forecasts (ECMWF). River run-off data have been deduced from a Hydrological Discharge Model (HDM) forced with ECMWF data as well. While submonthly mass variability is generally insignificant for GRACE de-aliasing purposes in most oceanic regions, monthly mean mass signals of up to 2 hPa occur in the Arctic Ocean during the melt season. Additionally, from freshwater fluxes due to precipitation, evaporation and river run-off the seasonal variations of total ocean mass are calculated. Correspondence with observed mass variations deduced from monthly GRACE gravity solutions indicates that a combination of ECMWF, HDM and OMCT allows a consistent prognostic simulation of mass exchanges among the atmosphere, ocean and conti-

[1] Bernd Richter: Bundesamt für Kartographie und Geodäsie / Federal Agency for Cartography and Geodesy (BKG), Referat G1 "Grundsatz und globale Referenzsysteme", Richard-Strauss-Allee 11, D-60598 Frankfurt a.M., Germany, Tel. +49-69-6333-273, Fax +49 - 69 - 6314905-20, e-mail bernd.richter@bkg.bund.de

[2] Florian Seitz: Deutsches Geodätisches Forschungsinstitut (DGFI), Alfons-Goppel-Straße 11, D - 80539 München, Germany, Tel. +49 - 89 - 23 031 12 92, Fax +49 - 89 - 23 031 1240, e-mail seitz@dgfi.badw.de

nental hydrosphere. Thus, interpretations of GRACE based mass anomalies should account for both regional and global river run-off effects (DOBSLAW and THOMAS 2007).

More detailed investigations concerning atmosphere, ocean and hydrology can be found in the publications mentioned below.

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Earth Rotation – Theory and Analysis

M. Thomas[1], M. Soffel[1], H. Drewes[2]

1. Joint research activities

In order to organize joint research activities in "Earth rotation and global dynamic processes" in Germany, since the beginning of 2006 ten related sub-projects are supported by the German research funding organization DFG (Deutsche Forschungsgemeinschaft) in the frame of a research unit (Müller et al., 2005). Based on the general survey of Schuh et al. (2003) exposing the present state as well as necessary milestones for future research work concerning modelling, observation and analysis techniques, the main objective of this coordinated project is a comprehensive description and explanation of underlying physical phenomena contributing to variations of earth rotation by taking into account consistently the interactions and coupling mechanisms of the various sub-systems of the earth. Such an integral treatment of earth rotation based on existing and new observational data became possible by comprising experts of observation techniques, data processing and analysis as well as in particular modelling. The research unit with participating scientists and institutions from geodesy, geophysics, meteorology, and oceanography will provide significant contributions to international activities and programs such as GGOS (Global Geodetic Observing System) and GMES (Global Monitoring for Environment and Security).

In close cooperation with the research unit an earth system model for physically consistent simulations of atmospheric, oceanic and hydrological induced variations of earth rotation, deformation and gravity field is developed in a research project supported by DFG with participating German scientists from geodesy, meteorology and oceanography. The dynamical system model couples numerical models of the atmosphere, of ocean tides and circulation as well as of continental discharge considering consistent mass, energy and momentum fluxes between these near-surface subsystems of the earth in order to allow for explanations and interpretations of geodetically observed variations of global parameters of the earth.

2. Theory of earth rotation

2.1 General studies

A detailed overview of theoretical and observational foundations of earth rotation studies, a review of the present state of modelling and observation as well as a specification of needs for future research projects was given by Schuh et al. (2003).

Engels (2006) describes various formulations of the momentum and angular momentum balance on the basis of elements of continuum mechanics. He estimates the impact of second order terms, referring to, e.g., the earth´s flattening and incremental inertial forces, on the equations of polar motion and polar wandering derived from the balance equation of angular momentum and discusses the effects arising from neglecting these second order terms on the angular velocity vector of a homogeneously layered, spherical, viscoelastic and rotating earth affected by surface mass loads. Engels (2006) comes to the conclusion that the classical "spherical solution" exclusively differs from his enhanced solution with respect to higher order terms of the earth´s flattening.

Jochmann (2003) studied the effect of assumed mass redistributions on the Chandler period and found that large variations of the Chandler period of several days detected by several polar motion time series analyses are unlikely, and that it is sufficient to assume an invariable period for currently available time series.

Seitz (2004) developed the non-linear gyroscopic Dynamic Model for Earth rotation and Gravity (DyMEG) based on a triaxial ellipsoid of inertia and driven by lunisolar torques and consistent atmospheric and oceanic angular momenta in order to investigate interactions between geophysically and gravitationally induced polar motion and the earth´s free wobbles. DyMEG reproduces the period and damping of the earth´s free polar motion (Chandler wobble) from rheological and geometrical parameters by solving the Liouville equation numerically as an initial value problem. Since spectral analyses of both atmospheric and oceanic excitations gave no hint for increased power in the Chandler frequency band, Seitz et al. (2004) concluded that stochastic signals in the climate dynamics as caused by the weather and oceanic mass redistributions are a sufficient source to maintain the amplitude of the earth´s free wobble by resonant interaction. Depending on the quality of the excitations, the correlation between the numerical results for polar motion from DyMEG and IERS data reach up to 99% (Seitz, 2005; Seitz et al, 2005). In order to assess the dependence of the numerical solution on the initial values and rheological or geometrical parameters like Love numbers and the earth´s principal moments of inertia, Seitz

[1] Maik Thomas / Michael H. Soffel: Institut für Planetare Geodäsie, Technische Universität Dresden, Helmholtzstr. 10, D-01062 Dresden, Germany, Tel. +49 -351 - 4633 4200, Fax +49 -351 - 4633 7019, e-mail maik.thomas@tu-dresden.de / michael.soffel@tu-dresden.de

[2] Hermann Drewes: Deutsches Geodätisches Forschungsinstitut (DGFI), Alfons-Goppel-Str. 11, D-80539 München, Germany, Tel. +49 - 89 - 23031-1106, Fax +49 - 89 - 23031 1240, e-mail drewes@dgfi.badw.de

and KUTTERER (2005) performed a sensitivity study revealing that the pole tide Love number k_2 is the most critical parameter, while the dependence on other parameters is marginal.

2.2 Excitation of earth rotation by geophysical fluids

ENDLER (2007) investigated the relationship between interannual variations in Length of Day (LOD) and selected El Nino/Southern Oscillation (ENSO) events. The study confirms that changes in the atmospheric angular momentum due to zonal winds are well correlated with LOD variability on timescales varying between several days and years. Strong correlations (at the 99% significance level) between the interannual amplitudes of LOD and the atmospheric wind term with sea-surface temperatures and selected ENSO indices clearly demonstrate a significant relation between interannual LOD variability, zonal atmospheric wind anomalies and the ENSO phenomenon. Although the overall correlation between LOD and ENSO is significantly varying in time depending on specific characteristics of the individual ENSO event, there is evidence that observed variations in the amplitude of LOD can be used as an indication for changes in the low and high frequency spectrum of hemispheric circulation systems led off by warm ENSO events. (LEHMANN et al., 2007).

SEITZ et al. (2005) and STUCK et al. (2005) investigated the role of atmospheric and oceanic dynamics in exciting polar motion in the annual and Chandler wobble frequency band by means of simulations with the gyroscopic model DyMEG consistently forced with output from the atmospheric climate model ECHAM and the ocean model OMCT. According to STUCK et al. (2005), the annual oscillation of polar motion is predominantly due to atmospheric pressure forcing, while the motion component is less important. A regional statistical analysis of AAM turned out that strong annual pressure variations over Asia, in particular at the Himalayas, is the primary component responsible for accelerating forced polar motion. Both STUCK et al. (2005) as well as SEITZ et al. (2005) came to the conclusion that stochastic processes in atmosphere and ocean are sufficient to excite the Chandler wobble. Neither a significant nor at least an increased signal in the frequency domain of 14 to 16 months was found and regional statistical analysis of angular momentum gave no hint for an oscillation with a typical timescale of 14 to 16 months. This is in agreement with the findings of THOMAS et al. (2005) who calculated power spectral densities from effective angular momentum functions deduced from various consistent model combinations (NCEP/MIT, NCEP/ECCO, ECHAM/OMCT). The investigated model combinations led to similar excitation power in the Chandler frequency band always exceeding the observed power.

The impact of oceanic mass redistributions due to pressure loading of atmospheric tides and gravitational tides at frequencies S_1 and S_2 was estimated by THOMAS et al. (2007) by means of simulations with OMCT driven by operational atmospheric data provided by ECMWF. The study demonstrates that ECMWF´s 3-hourly forecasts can be used to represent atmospheric mass redistributions and corresponding oceanic responses down to semidiurnal timescales and, consequently, to determine short-term effects of the atmosphere-ocean system on earth´s rotation. In contrast to, e.g., altimetry observations, the applied method principally allows a separation of effects due to gravitational and pressure tides.

From simulations with the Hydrological Discharge Model (HDM) WALTER (2005) deduced hydrologically induced excitations of earth rotation on seasonal to decadal timescales. Although the model simulations were higly sensitive to applied atmospheric forcing conditions, the results generally agreed with respect to the annual excitation of LOD, suggesting that about 25 µs of the annual amplitude have to be attributed to hydrological mass redistributions.

Applying the high-resolving unconstrained ocean model TiME forced by the complete lunisolar tidal potential derived from ephemerides, WEIS (2006) estimated the effect of several partial tides and shallow-water tides on earth rotation. Although the unconstrained model generally overestimates tidal amplitudes, the high-resolving real-time model agreed better with data assimilation models than partial tide model approaches. The total energy dissipated by the complete tidal oscillation system was estimated by WEIS (2006) to be 4.8 TW; the contribution of ocean tides to tidal friction was calculated to be 4.1 TW, while other recent studies agree on a lower value of 3.0 TW. However, some less significant partial tides, which had not been included in any modelling study, so far, were in excellent correspondence with results from both VLBI and GPS measurements with correlations of 90-96%. The effects of shallow-water tides on UT1 and polar motion turned out to be about three orders of magnitude lower than major astronomical partial tides, but should be above the detection limit of modern observation techniques within the near future.

2.3 Internal processes

One part of the earth rotation theory concerns the modelling of the influence of core processes (e.g. fluid motions, electromagnetic forces) on the earth's rotation. To this regard, GREINER-MAI et al. (2003) gave an outline about appropriate methods, results and unsolved problems.

To determine core motions and coupling torques from the geomagnetic field, it is necessary to extend the geomagnetic field from the earth's surface to the core-mantle boundary through an electrically conducting mantle. To solve this problem, a new inversion method for the induction equation of the mantle was developed until 2002. GREINER-MAI et al. (2004) have extended this method for determining the geomagnetic field in a differentially rotating upper core layer.

GREINER-MAI et al. (2003) discussed a kinematical model of forced inner-core wobble (ICW) by which the decadal variations of polar motion may be explained. Complementary, GUO et al. (2005a) checked the detectability of a free ICW with a period of about 6 years in the measured variations of the gravity field and polar motion. They found no firm evidence of the ICW in polar motion data used, which have an accuracy of few milliarc seconds.

3. Combination of different observation techniques

Earth orientation parameters (EOP) based on homogeneous and continuous VLBI and GPS data were consistently combined by THALLER et al. (2006b) using technique-specific datum-free normal equation systems. Especially the rigorous combination of UT1-UTC and LOD delivered by VLBI and GPS revealed that both techniques perfectly complement each other and the applied combination did not suffer from systematic effects present in the GPS-derived LOD values. The local geodetic ties between GPS and VLBI antennas generally play an essential role within the inter-technique combination. Several studies already disclosed non-negligible discrepancies between terrestrial measurements and space-geodetic solutions. THALLER et al. (2006b) demonstrated to what extent these discrepancies propagate into the combined EOP solution.

An overview of the combination studies performed by the Forschungseinrichtung Satellitengeodäsie der TU München (FESG) and the Deutsches Geodätisches Forschungsinstitut (DGFI) based on the data of the continuous IVS campaign CONT02 was given by THALLER et al. (2006a). The co-operation of the two institutions established the basis for a detailed adaption of GPS and VLBI software concerning models and parameterization to avoid systematic differences between the technique contributions. Regarding sub-daily earth rotation parameters the study emphasizes that a combination of the space techniques improves the results compared to single-technique solutions significantly. Furthermore, THALLER et al. (2006a) described a combination scheme for long sub-daily EOP time series from VLBI and GPS removing the weakness of UT1 estimations of satellite techniques and, consequently, offering the opportunity to study sub-daily tidal excitations and the influence of high-frequency or episodic geophysical effects on earth rotation.

In a joint effort the Technical Universities of Munich and Dresden performed a reprocessing of a global GPS network over the last decade in order to dispose existing inhomogeneities and inconsistencies of GPS time series of global geodetic parameters due to changes at the individual International GNSS Service Analysis Centers hampering geophysical interpretations of these long time series. According to STEIGENBERGER et al. (2006), first results of the reprocessing of 11 years of data showed significant improvements in the quality and homogeneity of estimated parameters, and formal errors of sub-daily earth rotation parameters could be reduced by 30%. In addition, advanced modelling approaches of second- and third-order ionospheric corrections and absolute antenna phase center corrections for receivers and satellites were tested to achieve further improvements.

4. Analysis and prediction

Results of the analysis of earth rotation data derived from the continuous VLBI campaign CONT02 were presented by HAAS and WÜNSCH (2006). Regarding high-frequency variations, 40-60% of polar motion and about 80% of UT1 could be explained by the ocean tide model of Ray. The remaining residuals were found to be on the level of several tens of micro-arcseconds. So far, they cannot be reproduced completely by models based on non-tidal angular momentum, atmospheric tides and luni-solar torques acting on the tri-axial earth. However, the diurnal signal detected in polar motion residuals could partly be explained by models due to non-tidal angular momentum and atmospheric tides. In the residuals of polar motion from CONT02 the authors identified third-diurnal variations close to the S_3 tide constituent with retro- and pro-grade amplitudes on the order of 40 mas, what is much larger than predictions based on atmospheric effects. With respect to the diurnal frequency band in UT1 the agreement between theoretical models and observations was also poor and the empirical values were generally larger than the modeled ones.

GUO et al. (2005b) investigated the double peak of the Chandler wobble (CW) in the spectrum of polar motion by comparing the polar motion data series (annual wobble removed) with a synthetic double-frequency CW time series. They observed a reasonable agreement between their peak times, which is an argument for the hypothesis of a double frequency CW, but is inconclusive with regard to whether the CW really has two frequencies. For the determination of the spectral properties of polar motion data a folding averaging algorithm (FAA) presented by GUO et al. (2005c) was used.

By means of an adaptive network based fuzzy inference system (ANFIS), AKYILMAZ and KUTTERER (2003, 2004) studied the short-term prediction of earth rotation parameters up to 40 days into the future; applying a similar approach, AKYILMAZ and KUTTERER (2005) extended the prediction period to one year. After removing well-known influences such as solid earth and ocean tide effects as well as seasonal atmospheric variations from the daily time series ERP C04 provided by IERS, the residual values were used for both training, i.e., optimization of parameters, and validation, i.e., comparison of predicted data with independent observed data, of the network. A comparison of predicted LOD and polar motion values with corresponding results from other methods, e.g., artificial neural networks (ANN), revealed root-mean-square errors which were equal or even lower than those from the other considered methods. The authors emphasized that the advantage of the applied prediction method lies not only in the high precision, but also in a comparatively easy handling. However, despite its significantly reduced complexity, ANFIS modelling is still more complicated than several other methods, such as, for example, the one used in the IERS EOP service.

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Sea Level and Ice Sheets

R. DIETRICH[1]

Mean sea level and sea level variations

The improvements in satellite altimetry in the last four years provided excellent opportunities to study the mean sea surface and its temporal variations. In this context interdisciplinary aspects became more and more important. The global sea level change as seen by altimetry, GNSS and tide gauge measurements has been investigated in detail (BOSCH 2005). The different effects in sea level variability were discussed by FENOGLIO-MARC and GROTEN (2003). The relation between bottom pressure, vertical structure of the ocean and sea level has also been studied (VINOGRADOVA et al. 2007) A combination of altimetry and satellite gravity allowed the estimation of the steric component in sea level variations (LOMBARD et al. 2006).

Regional studies of sea level variations were carried out for the North Atlantic (KUHN et al. 2005), the Mediterranean (TSIMPLIS et al. 2005, FENOGLIO-MARC et al. 2006) and the Baltic Sea (NOVOTNY et al. 2005).

Verification of mean sea level variations by combination of techniques

The intercomparison of different observation techniques and models is necessary in order to detect technique-dependent errors and biases in a suitable procedure as well as possible unmodeled effects. The range of investigations covers ionospheric corrections in satellite altimetry (BRUNINI et al. 2005), altimeter biases of different missions as determined in the Mediterranean (FENOGLIO-MARC et al. 2003) and the combination of observations and an oceanographic model in the Baltic Sea (NOVOTNY et al. 2006).

The relation of sea level variations and vertical crustal movements has been studied in detail in the Mediterranean (FENOGLIO-MARC et al. 2004).

Polar Ice Sheets

The polar ice sheets are of cruicial importance as a major component of sea level change and as an indicator for climate change. Several regional studies were carried out in order to investigate surface geometry, dynamics and mass balance in specific areas.

In Antarctica, the ice shelves represent sensitive indicators to climate changes. The Nivlisen, located in the Atlantic sector of the Antarctic coast, was studied by combining geodetic and glaciological observations (HORWATH et al. 2006). The tidal interaction of the Mertz glacier was investigated using remote sensing and in-situ observations (LEGRESY et al. 2004).

Only recently discovered, the Antarctic subglacial lakes attracted great attention as remarkable objects of joint international research activities. For the largest one, the 250 km long Lake Vostok in East Antarctica, the surface geometry has been determined from radar altimeter data (RÖMER et al. 2007). Furthermore, the glaciological flow regime (WENDT et al. 2006) and tidal effects within the lake were determined (WENDT 2005, WENDT et al. 2005).

In the Arctic, the large glaciers of the Greenland Ice Sheet represent one main topic of research. The largest glacier there, the Jakobshavn Isbrae, shows an acceleration of flow velocity from 20 m/day in 1995 up to 45 m/day in 2004 with corresponding effects on sea level (MAAS et al. 2006, DIETRICH et al. 2007).

The potential of GNSS reflections over ice sheets for glaciological investigations has been compiled in a feasibility study (WIEHL et al. 2003).

Geodetic Research in Arctic and Antarctic Regions

The geodetic research in polar regions, which has been intensified recently due to the International Polar Year 2007/2008, contributes also to the geodetic tasks in global scale. This includes especially the reference frame and the detection of horizontal crustal movements in Antarctica (DIETRICH et al. 2004) as well as ice-induced vertical crustal movements in Antarctica (SCHEINERT et al. 2005, 2006) and Greenland (DIETRICH et al. 2005).

SASGEN et al. (2007a) determined constraints on the present-day mass-balance and the ongoing glacial-isostatic adjustment (GIA) in Antarctica using the GRACE gravity-field time series. The approach involved noise reduction in the GRACE gravity fields based on the statistical analysis of the temporal variability of Stokes potential coefficients (MARTINEC et al., 2007) and optimal smoothing of the gravity field (SASGEN et al., 2006). Additionally, a method for the evaluation and combination of the GRACE gravity-field solutions based on an a priori model was proposed (SASGEN et al., 2007b).

Predictions describing the prominent geoid changes arising from present and past glacial changes in Antarctica (SASGEN et al., 2005) and Greenland (FLEMING et al., 2004) were made and, for Antarctica, adjusted to the noise-reduced GRACE observations. SASGEN et al. (2007a)

[1] Reinhard Dietrich: Institut für Planetare Geodäsie, Techn.ische Universität Dresden, Mommsenstraße 13, D - 01062 Dresden. Germany, Tel. +49 - 0351 - 463 346 52, Fax +49 - 351 - 463 370 63, e-mail dietrich@ipg.geo.tu-dresden.de

observed that the resulting masschange estimates vary significantly with respect to the GRACE release considered, with the propagated errors underestimating these uncertainties. However, it was demonstrated that for the strongest signal, which is associated with ice-mass loss in the Amundsen Sea Sector, the uncertainties lie below ca.10%.

Another important activity in Antarctica, which is mainly based on airborne gravimetry, is the regional improvement of the geoid (SCHEINERT 2005). The determination of atmospheric water vapour in Antarctica will support the validation and improvement of climatological models (VEY et al. 2004).

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International Earth Rotation and Reference Systems Service (IERS)

B. RICHTER[1]

Since 2001, the IERS Central Bureau (CB) is hosted and funded by Bundesamt für Kartographie and Geodäsie (BKG). It organizes and documents the IERS Directing Board Meetings and coordinates the work of IERS in general. The IERS CB organized IERS Workshops on site co-location (Matera, Italy, 23-24 October 2003), on the IERS Combination Pilot Project (Napa, CA, USA, 11 December 2004), on Combination (Potsdam, Germany, 10-11 October 2005), and on Global Geophysical Fluids (San Francisco, CA, USA, 6-7 December 2006). The CB publishes and distributes IERS Technical Notes, IERS Annual Reports, and IERS Messages. For this, a user database with about 3000 addresses is being maintained.

The CB maintains the dynamic and database-driven IERS Data and Information System to coordinate and organize the data and information flow between the participating institutions and the users of the IERS. The system presents information related to the IERS and the topics of Earth rotation and reference systems and archives all products of the various IERS Product Centres. As the central access point to these products it provides tools for search within the products (data and publications), to work with the products and to download the products.

The IERS Data and Information System has been developed at BKG in the framework of the Geotechnologien project “Integration of space geodetic techniques and development of a user centre for the IERS”. It is the basis for the development and implementation of a German contribution to the “Global Geodetic Observing System (GGOS)” realising a central interface to transfer information between the highly complicated system of measurement and analysis procedures and the users. In the follow-on Geotechnologien project “Integration of Space Geodetic Techniques as the Basis for a Global Geodetic-Geophysical Observing System (GGOS-D)” the system is being extended to permit the exchange and the near real-time provision of data and products of a global observing system.

Within the DFG Research Unit “Earth Rotation and Global Dynamic Processes” an “Earth Rotation Information System (ERIS)” is being developed at BKG. ERIS will be the interface for all projects involved in this research unit as central information, communication and database system. As a virtual Earth rotation system for geodetic and geoscience applications ERIS will organize a software package to describe and visualise the rotation of the system Earth based on the state of the art models and the combination of the various models describing the single components affecting the Earth rotation.

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[1] Bernd Richter: Bundesamt für Kartographie und Geodäsie / Federal Agency for Cartography and Geodesy (BKG), Referat G1 "Grundsatz und globale Referenzsysteme", Richard-Strauss-Allee 11, D - 60598 Frankfurt a.M., Germany, Tel. +49 - 69 - 6333-273, Fax +49 - 69 - 6314-905-20, e-mail bernd.richter@bkg.bund.de

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COMMISSION 4

POSITIONING AND APPLICATIONS

Overview and Highlights

M. BECKER[1], J. IHDE[2]

The main highlights in the past four year in view of positioning and applications was the advent of GNSS real time data and products in a world-wide standard (NTRIP), the first measurements with the new European GALILEO satellite GOIVE A and the related developments, the deeper understanding of antenna effects and multipath and the development of high sensitivity hard- and software receiver technology. Last but not least the atmospheric sounding with GPS and the CHAMP, GRACE and COSMIC satellites entered in its operational stage, a new pillar of geodesy. In the sequel some major topics are summarized and highlighted from the complete list of new research activities in the field of Commission 4 from the following chapters.

With regard to the IERS and reference activities the VLBI groups with the analysis coordinator's office at the Institute for Geodesy and Geoinformation of the University of Bonn (IGGB) contributed to the new ITRF2005 by solutions and rigorous combination of input series produced by the IVS Analysis Centers. The entire SLR data from 1993 to 2005 data and combined products, which are maintained at CDDIS and at DGFI (EUROLAS Data Centre, EDC) were used for a complete re-processing and re-combination to serve as input for ITRF2005.

German research groups contributed a great deal to the development and first implementations of the European satellite navigation system GALILEO. Major advancements were introduced in the definition of signal structures which lead to largely reduced multipath and still have the interoperability with GPS, in particular the E5-signals exhibit a small multipath error due to their large bandwidth. The latest signal design using MBOC (Modified Binary Offset Carrier) modulation is a breakthrough which will affect the future GPS development as well. However, it was also shown, that near field multipath can still be a thread to geodetic applications. In connection with the large number of new frequencies available with GALILEO, a wide spectrum of studies on the use of multi carrier ambiguity resolution techniques and the impact on the RTK and real time active reference networks was published. In view of positioning itself two major topics were under investigation, the precise point positioning and state space approach for geodetic applications and the entirely kinematic satellite POD (precise orbit determination) by geodetic-quality GPS receivers. In combination with improved sensors, such as accelerometers, star trackers and with new observation types such as precise intersatellite range- or range-rate measurements the precise determination of absolute and relative orbits of satellites and satellite pairs, respectively was significantly improved.

The advances in computer speed and data processing allowed for the realization of a software receiver by the group of the University of the Bundeswehr Munich. In Particular the research on the signal acquisition and tracking techniques like vector delay lock loops, multi-correlators or algorithms for bit synchronisation were studied. The techniques for direct multipath monitoring or the inversion of the software receiver as signal source for GNSS simulators were developed. To assist GNSS receivers in low signal strength and high dynamics scenarios the deep coupling of inertial sensors can be of importance for aiding the tracking.

New applications, like indoor use of (assisted) GPS by high sensitivity and software-receivers, open new fields and a number of new approaches, like digital GNSS signal postprocessing and the choice of optimal GNSS signals and codes in future GNSS, as well as alternative methods and positioning techniques such as wireless LAN were studied in the last four years. Pseudolites may turn out to be essential for particular applications with emphasis on robust and accurate height information, their error characteristics and specific applications were evaluated in several studies, among them the particular case of the implementation of the GALILEO test bed GATE in Berchtesgaden.

All major error sources were subject to improvements in modeling and mitigation by new research work in the past four years. The inclusion of corrections for higher order ionospheric effects, e.g. in the re-processing effort of the IGS network since 1994 at Munich and Dresden, showed improved results for the global network. RTK and ambiguity resolution were improved by new models for the inclusion of external information on the ionosphere in the preprocessing. In particular the introduction of newly developed tropospheric mapping functions improved the error budget of positioning and in future even tropospheric modeling based on GNSS observations on moving platforms may be feasible. New approaches for multipath calibration at particular sites in order to prevent the antenna-change related offsets were published and may lead to more reliable absolute GNSS coordinates. Major contributions were made from German groups to the calibration of both satellite antennae and receiver antennae. The estimation of the satellite antennae phase center variation, in combination with the absolute calibration of ground based antennae

[1] Matthias Becker, TU Darmstadt, Institut für Physikalische Geodäsie, Petersenstrasse 13, D-64287 Darmstadt, Germany, Fax +49 - 6151 - 164512, Tel. +49 - 6151 - 163109, e-mail becker@ipg.tu-darmstadt.de

[2] Johannes Ihde: Bundesamt für Kartographie und Geodäsie (BKG), Richard Strauss Allee 11, D - 60598 Frankfurt a.M., Germany, Tel. +49 - 69 - 6333 -206, Fax +49 - 69 - 6333 -425, e-mail johannes.ihde@bkg.bund.de

dramatically improved the coherence of GNSS to the other geodetic space techniques results.

During the past four years the German research institutes mainly consolidated their contributions to the network of continuously recoding permanent stations. The GeoForschungsZentrum Potsdam (GFZ) extended its High-Rate/Low-Latency (HR/LL) GPS ground tracking network established jointly by GFZ and JPL to ensure adequate ground data availability for CHAMP and GRACE satellite missions to 15 stations. New real time stations are planned and partly installed within the South East Asia-Indian Ocean region as part of the Tsunami Warning System GITEWS. The large scale network SAGA for geodynamics in the Southern and Central Andes was extended and densified with new continuous sites and epoch stations with an anticipated resolution of 50 km in seismic gap regions. The Federal Agency of Cartography and Geodesy (BKG) upgraded part of its IGS and EUREF sites and installed a continuous local monitoring network for the TIGO fundamental station in Conception, Chile.

Several Universities participated in international research and programmes which included the installation of new permanent GPS stations. TU Dresden was active in the Arctic Peninsula region. TU Karlsruhe focussed on Brazil, the Vranca deformation zone in Romania and the Upper Rhine-graben in Germany. TU Darmstadt installed one permanent site in cooperation with the University of Bucharest in Oradea, Romania in Romania as part of the Central European Geodynamic Reference Network CEGRN.

A major novel approach was the rapid development of the NTRIP-based streaming real time GNSS data system by BKG. At the beginning of 2007 raw data or corrections of about NTIRP 1850 stations were available at 80 casters worldwide. Due to the standardization of the NTRIP transfer protocol in September 2004 a huge user community in science and industry utilizes these data stream. New applications for real time clock and orbit products are under development. The BKG German base network GREF with its 19 stations is completely transferred to the real time streaming data delivery by use of NTRIP and corresponding DGPS correction data are streamed via NTRIP casters as well.

GNSS based techniques are used for atmospheric sounding since several years but within the reporting period a breakthrough for the use of GPS based atmospheric data for various applications in atmospheric research occurred. Since 2006 the GPS occultation data from COSMIC, GRACE-A and CHAMP are operationally used of by the European Centre for Medium-Range Weather Forecasts (ECMWF) to improve global weather forecasts. GFZ Potsdam contributed significantly by the CHAMP satellite mission, data analysis techniques, applications and also assimilation techniques were developed and improved. Presently GRACE and the data of the COMSIC constellation are under investigation and in preparation for the operational use.

Space based applications are supported by the continuous provision of near-real time atmospheric data from a regional German network, processed at GFZ for inclusion to the European E-GVAP action, to push the use of GPS ground data for numerical weather prediction (EUMETNET-GPS water vapor program, within the network of the European Meteorological Services). Since 2006 these data are assimilated at MeteoFrance and additional weather services will join in 2007.

Research is dedicated also to the novel application of reflected GNSS signals in the altimetry/scatterometry approach, where lake levels were monitored with an accuracy of ~2 cm. Further promising perspectives are ground and space based applications in geoscience and atmospheric research, e.g. on ice surface properties (roughness), ice coverage of oceans, sea surface heights, significant wave height and wind speed/direction above sea surfaces are feasible and under investigation.

Space Geodetic Techniques (VLBI, LLR, SLR, DORIS)

A. NOTHNAGEL[1]

VLBI

The activities of the research groups in the field of geodetic and astrometric VLBI in Germany are being coordinated within the "Forschungsgruppe Satellitengeodäsie" (Research Group Satellite Geodesy – FGS). Since the inauguration of the International VLBI Service for Geodesy and Astrometry (IVS) on February 11, 1999, all groups have become members and are making significant contributions to this international body (IVS 1999). The VLBI observatories of Wettzell (Bavarian Forest), O'Higgins (Antarctic peninsula) and TIGO (Conception, Chile) are imbedded in the global observing activities and produce a large number of observations in different global and regional network configurations. The data is mostly correlated at the MPIfR-BKG-Correlator which is jointly operated by the Bundesamt für Kartographie und Geodäsie (BKG), the Max-Planck-Institut für Radioastronomie (MPIfR) and the Institute of Geodesy and Geoinformation of the University of Bonn (IGGB). The Deutsches Geodätisches Forschungsinstitut (DGFI) as well as BKG and IGGB maintain IVS Analysis Centers for various research activities in the field of geodetic and astrometric VLBI. At BKG (branch Leipzig) one of the three global IVS Data Centers is responsible for storing all VLBI observational data and IVS products to allow easy access by all users. In the period reported here, Germany was represented in the IVS Directing Board by two members, WOLFGANG SCHLÜTER (Chairman) and AXEL NOTHNAGEL (IVS Analysis Coordinator). The IVS Analysis Coordinator's office is hosted by the Institute of Geodesy and Geoinformation of the University of Bonn (IGGB). Here, the official IVS Earth orientation parameter products are generated from a rigorous combination of input series produced by the IVS Analysis Centers (NOTHNAGEL and STEINFORTH 2002). The results and more information are available at the IVS home page *http://ivscc.gsfc.nasa.gov* with a link to the IVS Analysis Coordinator's page.

BKG and FESG (Forschungseinrichtung Satellitengeodäsie der TU München) on behalf of the FGS continued their strong support for the VLBI community by operating the 20m VLBI facilities at the Fundamentalstation Wettzell, the VLBI module of TIGO at Concepcion/Chile and the 9m VLBI facilities of the German Antarctic Receiving Station (GARS) O'Higgins. All three telescopes have been heavily involved in the regular activities of the International VLBI Service (IVS). Wettzell and TIGO were employed in the weekly IVS observing programs all over the year(s), while GARS-O'Higgins was involved campaign-wise, as no continuous tracking could be implemented yet (SCHLÜTER et al. 1999a, SCHLÜTER et al. 1999b).

Space technique co-location by means of GNSS

For about ten globally distributed ESA tracking sites co-location ties for GPS sensors (IGS stations) and radio telescope antennae (for other space techniques like VLBI, SLR) were determined by means of GPS, total station and levelling measurements. Co-location ties are finally derived within ITRF at the mm accuracy level. A new algebraic approach for the indirect method to determine radio telescope antenna reference point and rotation axis parameters was developed (LEINEN et al., 2007). The VLBI telescopes at Wettzell, O'Higgins and Concepcion are co-located with GPS stations of the IGS and the ties are routinely checked by local ground surveys.

SLR

In Germany Satellite Laser Ranging was and still is carried out by the GeoForschungszentrum (GFZ) at its station Potsdam (Potsdam-3) and by the Bundesamt für Kartographie und Geodäsie (BKG) on behalf of the Forschungsgruppe Satellitengeodäsie (FGS) at the Fundamental Station Wettzell employing WLRS (Wettzell Laser Ranging System). In Concepcion/Chile the SLR module of the Transportable Integrated Geodetic Observatory (TIGO-SLR) is operated by BKG in close collaboration with a Chilean consortium led by the University of Concepcion. The station Potsdam and Wettzell are network stations of EUROLAS. Potsdam, Wettzell and Concepcion are network stations of the International Laser Ranging Service (ILRS). All stations observed routinely with high efficiency with respect to the number of passes tracked per year and with respect to the quality. The TIGO SLR module was faced with some hardware problems of the Titan Sapphire Laser. Now, the laser is replaced by a Titan Sapphire Laser which has a repetition rate of 100 Hz. After the replacement in 2006, TIGO SLR now provides observations in two colours, infrared (850 nm) and blue (425 nm) as expected in the number of passes observed and in quality.

A new Laser Ranging System was designed for the Fundamental Station Wettzell, the so-called Satellite Observing System Wettzell (SOS_W), which will take over routine observations of satellites in a highly automated mode, continuously 24 h/day all over the year. The laser of SOS_W will have a repetition rate of 1 kHz and will allow laser ranging with two colours (infrared and blue) for troposphere

[1] Axel Nothnagel, Institute of Geodesy and Geoinformation of the University of Bonn, Nussallee 17, D-53115 Bonn, Germany, Tel. +49 - 228 - 733574, email nothnagel@uni-bonn.de

investigations. The system is in the construction phase, first observations are expected in 2008. The existing Wettzell Laser ranging system (WLRS) will be optimised for Lunar tracking and for tracking high orbiting satellites like the GNSS-satellites.

The ILRS Analysis Centres at BKG, DGFI, GFZ are routinely processing tracking data to the geodetic satellites Lageos-1/2 and Etalon-1/2 on a weekly basis. These solutions contain station coordinates and Earth Orientation Parameters (EOP). This processing includes also the computation of pass-dependent biases, which are published at the DGFI Homepage *http://www.dgfi.badw.de/dgfi/ILRS-AC/quality/index.html*. The output is generated in SINEX format for subsequent combination with other SLR solutions. At the ILRS/AWG meeting in June 2004 in San Fernando (Spain) ASI (Italy) has been nominated as the primary ILRS combination centre while DGFI was selected as the backup combination centre. Both combination centres are responsible for the weekly combination of the contributions from the individual analysis centres. The combined products are delivered to the ILRS Data Centres which are maintained at CDDIS and at DGFI (EUROLAS Data Centre, EDC). The entire SLR data from 1993 to 2005 has been re-processed and re-combined to serve as input for ITRF2005.

LLR

At the IfE (Institut für Erdmessung, Institute of Geodesy, Leibniz University Hannover), which is an official lunar analysis center of the ILRS, the software to analyze the LLR data has been converted from Fortran 77 to Fortran 90 (KOCH 2005) in spring 2005. A further item in the past years was the implementation of a new integrator for the numerical integration of the ephemerides of the main solar system bodies and the dynamical partials with sufficient accuracy. With the new software package, standard solutions for the determination of the unknown parameters were carried out using all LLR measurements between 1970 and 2006, about 16, 000 normal points. Besides the 'Newtonian' parameters of the Earth-Moon system, many relativistic effects were investigated such as the validity of the equivalence principle or predictions of alternative theories of gravity (e.g. MÜLLER et al. 2006).

In May 2006 a new LLR project imbedded in a German research unit of the DFG (German Research Foundation) dedicated to "Earth rotation and global dynamic processes" has been set up.

In cooperation with U. SCHREIBER, Wettzell, and J. OBERST, DLR, IfE started to investigate the poor observational conditions in LLR and to think about possible improvements by new installations on the Moon. In this respect investigations of how the various reference frames are affected have been performed (MÜLLER et al. 2007).

In the future, LLR results shall be provided to a larger user community via ILRS and IERS. The contribution of LLR for geodetic applications and its visibility shall further be improved by J. MÜLLER (IfE) who serves as LLR representative in the ILRS Governing Board and as ILRS representative in the Directing Board of the International Earth Rotation and Reference Systems Service (IERS) since 2006.

DORIS

No major activities related to the French DORIS (Doppler Orbitography and Radiolocation by Satellite) system were observed in Germany.

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GNSS Positioning

T. SCHÜLER[1]

Introduction

This section summarises scientific achievements in the field of “GNSS positioning” which comprises efforts related to the definition and optimisation of Global Navigation Satellite Systems (GNSS), in particular GALILEO, studies of GNSS interoperability and combined positioning using several satellite navigation systems synchronously. Furthermore, algorithms are currently refined for precise geodetic positioning regarding the new innovations in satellite navigation. In this particular working field, the correct resolution of the integer ambiguity parameters is essentially required which will certainly be aided by observations on more than 2 carrier frequencies and a better signal structure. Nevertheless, although satellite positioning has greatly revolutionised geodetic work, the fusion of GNSS and INS can play an important role in precise positioning – at least for those geodetic applications setting high requirements on availability and continuity of service. Finally, some typical geodetic positioning applications are briefly mentioned with links to sections within this report that portray those techniques more in detail.

GNSS – Overview

Substantial changes are going on in order to improve existing or establish new global satellite navigation systems. The *modernisation of GPS* which is already in progress: Three Block IIR-M (replenishment-modernised) satellites have been placed in orbit since December 2005 and broadcast a civil signal on the second carrier frequency now (L2C). A full constellation of L2C-capable satellite is expected by 2012 which will eliminate the current need to reconstruct the encrypted P-code that leads to relatively weak measurements of the L2 carrier phase in nowadays civilian GPS receivers. Further enhancements are planned with the Block IIF/III satellites, namely signals on a third frequency (L5; intended for civilian use) which will facilitate the ambiguity resolution process.

The *Russian satellite navigation system GLONASS* still suffers from weaknesses as it is far away from a global constellation of satellites and has an unfortunate FDMA design (frequency-division multiple access) making it not very attractive to precise kinematic users. However, marketing strategists have identified GLONASS as a promising candidate to fit well into market until the newcomers like GALILEO are ready, and the Russian government has expressed its will to re-achieve a global constellation with FOC (full operational capabilities) already in 2009/2010. Plans to modernise GLONASS are on their way featuring signals on a third frequency (L3 band) by 2008.

Europe has decided to build up its own GNSS called *GALILEO*. It is currently built up by the EU/ESA member states and is expected to become fully operational by 2012 offering several services on 3 major frequency bands, including an Open Service (OS) which will be basically available free of charge, a Commercial Service (CS) and a Public Regulated Service (PRS). The final constellation will consist of 30 MEO (Medium Earth Orbiting) satellites (including 3 passive spares). In-Orbit-Validation (IOV) is scheduled by the end of 2008 using 4 satellites. However, the launch of test satellite GIOVE-B is already substantially delayed and now scheduled for the end of 2007, whereas GIOVE-A was successfully placed in orbit in December 2005 in order reserve the needed frequency bands and to test parts of the critical navigation technology.

China also plans to establish a new GNSS called *Compass*. The very ambitious plans envisage operation by 2012 using a constellation of 5 geostationary (GEO) and 30 non-GEO satellites with 4 carrier frequencies. Three test satellites were sent into orbit between 2000 and 2003 and two “Beidou” satellites (Compass, version 1) are expected to be launched soon as a regional augmentation. (HEIN et al., 2007)

GNSS – Definition and Optimisation

All these changes and improvements depicted before will undoubtedly have a positive effect on geodetic GNSS positioning, and German scientists have taken the opportunity to actively contribute to the development and optimisation of the European satellite navigation system *GALILEO*. This work focuses mainly on the definition of signal structures and navigation codes appropriate for a state-of-the-art GNSS as well as the development of a default GALILEO tropospheric correction model (see section “Nuisance Effects on GNSS”). A number of articles presenting an overview of this new satellite navigation system have been published so far (EISSFELLER et. al., 2007; GERLACH, 2006; HEIN and PANY, 2003).

The GALILEO frequency and signal design can be briefly summarised as follows: Signals are emitted by the satellites on the E1-, E6- and E5-band. The Open Service has access to the signals in the E1- (identical centre frequency as GPS-L1) and E5ab-band which can be split into the sub-carriers E5a (identical centre frequency as the future GPS L5 signal) and E5b, although sophisticated receiver equipment will

[1] Torben Schüler: Universität der Bundeswehr München, Institut für Erdmessung und Navigation, Werner-Heisenberg-Weg 39, D - 85577 Neubiberg, Germany, Tel. +49 - 89 - 6004-2587, Fax +49 - 89 - 6004-3019, e-mail torben.schueler@unibw.de / dr_schueler@gmx.net

also be able to track the broadband signal E5ab without splitting the spectrum into sub-carriers. The E5-signals exhibit a particularly small multipath error due to their large bandwidth. Future combined GPS/GALILEO dual-frequency (L1/E1, L5/E5a) receivers can be manufactured without large technological efforts due to these inter-operability features. The Commercial Service will have a privileged access to the E6-signal featuring a particularly large data rate for additional services. The Public Regulated Service will use E6, too, but uses a different signal modulation. Like the modernised GPS signals, GALILEO will also offer a data-free pilot channel which simplifies carrier phase tracking leading to an increased performance regarding tracking stability (less cycle slips to be expected).

Almost all facets of the GALILEO signal design evolution are mirrored in the available scientific literature with contributions by HEIN et al. (2003), HEIN et al. (2004). Optimisation work followed (HEIRIES et al., 2005; HEIN et al., 2005a) and culminated in the latest signal design using MBOC (Modified Binary Offset Carrier) signal modulation which will also become an option in the *GPS modernisation programme* for reasons of interoperability (HEIN et al., 2006B; HEIN et al., 2006C; AVILA-RODRIGUEZ et al., 2006).

In addition to this research of signal optimisation leading to an easy use of both GPS and GALILEO civilian signals, investigations are also carried out to combine the protected GPS military and GALILEO Public Regulated Service (PRS; formerly GAS: Government Access Service) as described in HEIN and AVILA-RODRIGUEZ (2005), HEIN and AVILA-RODRIGUEZ (2006). Moreover, intensive interference computations were carried out in order to confirm that all existing GNSS can co-exist without any significant loss in service performance (WALLNER et al. 2006; WALLNER et al., 2005).

Combined GNSS Positioning

As already stressed, an added benefit of the innovations taking currently place in satellite navigation comes from the fact that GPS and GALILEO show a high degree of interoperability and can thus be easily combined in a GPS/GALILEO receiver. The advantages of both the dual satellite-constellation and the advances in signal design are outlined in AVILA-RODRIGUEZ et al. (2005) for a typical mass-market single-frequency GNSS receiver. Regarding precise static positioning for scientific purposes, work on the combined analysis of GPS and GALILEO signals has been carried out by HEINZE (2006), and with respect to the modelling of GPS and GALILEO observations by GRUBER (2006).

Ambiguity Resolution Techniques

Considerable work has been carried out regarding the improvement of GNSS positioning algorithms, in particular taking into consideration the expected benefits from the innovations of satellite navigation in the future.

The key to high-precision GNSS positioning is the quick and reliable (correct) ambiguity resolution. Future GPS will offer signals on up to 3 carriers (L1, L2, L5), GALILEO will offer signals on up to 4 carrier frequencies without any further costs (Open Service: E1, E5ab and sub-carriers E5a and E5b) and even 5 signals when the Commercial Service on E6 is used in addition. Many new signal combinations can be used to resolve ambiguities. Signals on nearby frequencies can be combined to form a "Super Wide Lane" (e.g. E5a and E5b or L5 and L2). This linear combination, a kind of "virtual signal", has a particularly large wavelength and could be easily fixed to its integer value by combination of code (pseudo-range) and carrier-phase measurements without any knowledge of the antenna position (geometry-free ambiguity resolution approach). Furthermore, noticeable improvements can be expected due to the fact that the improved signal structures for GALILEO and also for GPS L5 allow for a better reduction of the multipath errors by receiver-internal signal processing algorithms. This statement is particularly true for the broadband E5ab/E5a/E5b signals, whereas, in general, short-delay multipath signals – not infrequent in geodetic positioning – will still lead to significant errors (SCHÜLER et al., 2005b).

A number of authors outline the advantages of using measurements on more than 2 frequencies for ambiguity resolution. SAUER et al. (2004) report about test results using 3 (TCAR – triple carrier ambiguity resolution) in comparison to 4 carriers as offered by GALILEO; a multiple-carrier ambiguity resolution approach is shown in VOLLATH and SAUER (2004). Geometry-free resolution approaches for 3 and more carrier for both GPS and GALILEO are depicted in WERNER and WINKEL (2003). Further contributions comprise investigations on the difficulties in ambiguity resolution under multipath impact JOOSTEN and IRSIGLER (2003).

Positioning Algorithms

Remarkable efforts have also been devoted to precise positioning in general, in particular with focus to RTK (real-time kinematic) positioning, and also taking the improvements of the new satellite navigation systems into account. A clear tendency towards precise positioning utilizing active GNSS reference networks – which are currently established or already in operation in many countries – can be noticed (WILLGALIS, 2005; WILLGALIS et al., 2003).

Potential benefits from GPS modernisation and GALILEO are illustrated in (LANDAU et al., 2004; VOLLATH et al., 2004a; LANDAU et al., 2007). The deep impact on network real-time kinematic positioning is also stressed and questioned in CHEN et al. (2004). Network processing using federated sequential filter techniques is demonstrated by CHEN et al. (2003) in order to process large GNSS networks. The datum transition in real-time for services is dealt with in KUHLMANN and KÖTTER (2006). As most of these techniques require active GNSS networks, please also have a look on the corresponding section "Permanent GNSS Networks" of this report.

Ongoing work to improve the estimation models for satellite positioning is carried out by German scientists, in particular with respect to a realistic stochastic model of GPS observations. Work devoted to this topic comprises Bischoff et al. (2005; 2006) as well as Howind (2005). The impact of systematic errors on long baseline kinematic GPS processing and ambiguity estimation is dealt with in Schüler (2006).

Precise GNSS Positioning

GNSS is actively and broadly used for positioning in geodetic applications. Exemplarily, a few prominent uses are briefly mentioned here with links to other relevant sections of this national report.

A typical and – in terms of positioning accuracy – highly challenging application is *deformation monitoring* as well as the detection of geodynamic phenomena. An example for the detection and monitoring of regional deformation in the Rhine embayment due to coal mining activities can be found in Görres et al. (2006), displacements in the Upper Rhine Graben are investigated by Rozsa et al. (2005), for instance. Vertical ground-motion and intraplate settings in the Ardenne-Eiffel region are studied in Demoulin et al. (2005). Groups at the TU Karlsruhe and a number of other research institutions are active regarding GPS-based deformation analysis Adam et al. (2002). Furthermore, 3-dimensional plate kinematics in Romania can be found in Hoeven et al. (2004). Please also refer to section "Commission 3 – Earth Rotation and Geodynamics – Crustal Deformation and Geodynamics". Moreover, the stability of fundamental station Wettzell is monitored by a cluster of receivers in order to investigate local and environmental effects (Lechner, 2003; Lechner et al., 2003; Schlüter et al., 2005). A monitoring system for deformation of buildings like bridges with real-time capabilities is described by Hein and Riedl (2003). Further aspects of this engineering topic can be found in section "Applications in Engineering".

Secondly, a tendency towards an entirely kinematic satellite orbit determination – i.e. *orbit determination by GNSS positioning* – can be observed during the past few years since more and more low-Earth orbiting (LEO) satellites are equipped with geodetic-quality GPS receivers for POD (precise orbit determination). The determination of kinematic (and reduced-dynamic) trajectories for CHAMP, GRACE, Jason, COSMIC is exercised by (Svehla and Rothacher, 2003; 2005; Svehla and Földvary, 2006), for instance, with orbits computed for CHAMP and GRACE covering more than two years in the meantime. Also, ambiguity resolution for CHAMP and for baselines between the two GRACE satellites is subject of research (Svehla and Rothacher, 2003). Further information can be found in section "Satellite Orbit Modelling".

Finally, in recent years, the potential to exploit *low-cost GPS receivers* – that were originally manufactured for the consumer market – for geodetic purposes has been investigated in detail.

These receivers are typically L1-only devices and are therefore limited to short-baseline applications. In particular, GARMIN receivers offer an experimental output of PLL-related observations (like carrier-phase and Doppler shift measurements). Although these devices suffer from several limitations, e.g. half-cycle slips, centimetre-level point precision can be obtained from static observations (Schwieger, 2003; 2004; 2005; Schwieger and Wanninger, 2006).

GNSS/INS-Integration

Although GNSS offers many benefits to the geodetic community, it is clear that major disadvantages of this technique are related to availability and continuity of service (mainly due to obstacles leading to data gaps). For this reason, research regarding the integration of GPS and INS (Inertial Navigation Systems) is an ongoing topic within the community. (Kipka, 2006) describes such a combined surveying system that also integrates network concepts like area correction parameters and virtual reference station allowing to access active GPS reference networks (e.g. SAPOS). Further examples for GPS/INS-Integration can be found in section "Navigation".

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Nuisance Effects in GNSS

L. WANNINGER[1], S. SCHÖN[2]

Introduction

Observations of the signals from satellites of one of the GNSS (the US-American GPS, the Russian GLONASS, the future European Galileo and quite a few planned regional systems) are influenced by several factors which adversely affect the accuracy and reliability of the positioning results. The most important influences are ionospheric and tropospheric propagation delays, multipath from the surroundings of the receiving antenna, and antenna phase centre variations (PCV) of both the receiving and the transmitting antennae (cf. SEEBER 2003).

Ionospheric and tropospheric propagation delays can be reduced considerably by relative GNSS using a single reference station or even better a network of reference stations surrounding the observation site. Multipath and PCV, however, are station and antenna dependent effects. They are dealt with in the measurement procedure or by calibration.

During the past four years a considerable amount of research work has been carried out in the field of nuisance effects affecting GNSS observations. A selection of key publications is given in the text. A more extensive list is included in the references.

Ionospheric propagation delay

First-order effects of the ionospheric propagation delay are successfully removed by using dual-frequency observations (ionosphere-free linear combination). Higher-order effects are typically ~0-2 cm at zenith, larger for lower elevated satellites, but at the same time smaller for relative positioning applications. Nevertheless, corrections for the higher-effects can easily be obtained and may improve positioning results (FRITSCHE et al. 2005, MAINUL HOQUE, JAKOWSKI 2007).

Relative ionospheric propagation delays influences the reliability and success rate of ambiguity resolution even in case of dual-frequency observations. The pre-processing of the observation data of networks of reference stations does not only provide improved ionospheric real-time correction models but can also produce valuable information on the size of ionospheric residuals which will affect baseline processing (CHEN et al. 2003, WANNINGER 2004).

Tropospheric propagation delay

There are several approaches to reduce the influence of tropospheric propagation delays which mainly affect the height component of the positioning results: application of standard tropospheric corrections, relative positioning, estimation of tropospheric delays as additional unknowns etc. In practice these approaches are combined to yield precise positioning results.

Research work dealt with standard tropospheric models for Galileo (PÓSFAY, 2003, KRUEGER et al. 2004), comparison of tropospheric mapping functions (VEY et al. 2006) and radiometric measurements for validation studies (HÄFELE et al. 2004). Tropospheric modelling based on GNSS observations from moving platforms has been studied by SCHÜLER (2006a).

Multipath mitigation

The ability to discriminate between direct and reflected signal in the measurement process largely depends on the signal characteristics. New signals structures were analysed regarding their multipath performance in order to select appropriate signals for the Galileo system (IRSIGLER et al. 2004, PANY et al. 2005, ÁVILA-RODRIGUEZ et al. 2006).

An alternative approach for permanent stations or identical antenna set-ups is multipath calibration. Calibration of carrier-phase multipath effects caused by signals reflected in close vicinity (… 10-20 cm) of the antenna has been performed by WÜBBENA et al. (2006b). In-situ multipath calibration of an antenna and its surroundings has been published by DILSSNER et al. (2006).

Uncorrected multipath effects may cause an apparent height shift of up to approx. 1 cm in case of an antenna exchange. This phenomena has been observed e.g. in the German SAPOS network of permanent GPS-stations (KLEIN, KLETTE 2005, WANNINGER et al. 2006). It illustrates the unresolved difficulties precise height determination still faces.

Antenna phase centre variations

Many research groups contributed to a better understanding of the antenna phase centre variations (PCV) of both the receiving antennae and the transmitting antennae on-board the GNSS satellites. Receiving antennae are calibrated either in the field using the original GNSS signals (MENGE

[1] Lambert Wanninger: TU Dresden, Geodätisches Institut, D-01062 Dresden, Germany, e-mail lambert.wanninger@tu-dresden.de

[2] Steffen Schön: Leibniz Universität Hannover, Institut für Erdmessung, Schneiderberg 50, D-30167 Hannover, Germany, e-mail schoen@ife.uni-hannover.de

2003, WÜBBENA et al. 2006a) or in an anechoic chamber using artificial signals (CAMPBELL et al. 2004, GÖRRES et al. 2006, BECKER et al. 2006).

The data processing of regional or global GNSS-networks made use of so called relative PCV corrections until recently. Although it had been shown for several years that absolute corrections would be required (MENGE 2003, VÖLKSEN 2005) it lasted until 2006 to change the processing procedures of these large-scale networks. The processing of these networks also requires PCV corrections of the GNSS satellites. These corrections are estimated from the ground observations as additional unknowns in the adjustment procedure (SCHMID et al. 2003, SCHMID et al. 2005).

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Permanent GNSS Networks, including SAPOS

G. WEBER[1], M. BECKER[2], J. IHDE[1]

Contributions to Global and Regional Networks

During the past four years the German research institutes mainly consolidated their contributions to the network of continuously recording permanent stations. The GeoForschungsZentrum Potsdam (GFZ) extended its High-Rate/Low-Latency (HR/LL) GPS ground tracking network established jointly by GFZ and JPL to ensure adequate ground data availability for CHAMP and GRACE satellite missions to 15 stations. New real time stations are planned and partly installed within the South East Asia-Indian Ocean region as part of the Tsunami Warning System GITEWS. The large-scale network SAGA for geodynamics in the Southern and Central Andes was extended and densified with new continuous sites and epoch stations with an anticipated resolution of 50 km in seismic gap regions. The Federal Agency of Cartography and Geodesy (BKG) upgraded part of its IGS and EUREF sites and installed a continuous local monitoring network for the TIGO fundamental station in Conception, Chile.

Several Universities participated in international research and programmes which included the installation of new permanent GPS stations. Technical University (TU) Dresden was active in the Arctic Peninsula region. TU Karlsruhe focussed on Brazil, the Vranca deformation zone in Romania and the Upper Rhine Graben in Germany. TU Darmstadt installed one permanent site in cooperation with the University of Bucharest in Oradea, Romania as part of the Central European Geodynamic Reference Network CEGRN.

GNSS Data Centre

GNSS Data Centres are mandatory today in order to exchange all kinds of observations, meta-data and analysis results between analysis centres and product users. BKG operates for this purpose a GPS/GLONASS data centre for the European region and holds data from IGS, EUREF and national permanent GNSS projects. The data base system has been completely renewed in 2005 by replacement of the hard- and software. The new system provides now disk capability to hold all data online since the beginning of the IGS in 1992. For this purpose a comprehensive “reloading campaign“ was started in December 2005 in order to make files available in a uniform manner that were stored on the most different archiving media. The old data will be needed for projected “re-processings“ through IGS and other projects.

The new software design applies now an SQL data base to hold all meta-data. That enables to built dynamic websites as requested by the users. Extended browse and search functionality allow comfortable inquiries to fulfil user requests. This new system had been launched and switched online in July 2005.

NTRIP

The transmission format NTRIP was standardized in September 2004 at international level by the "Special Committee 104" of the "Radio Technical Commission for Maritime Services" (RTCM SC-104)”. An extension of the format to Version 2.0 is presently under development. For the aim of providing GNSS real-time data at the widest-possible global range, it is essential to support a broad palette of different approaches to communication and data transfer based on the flexible internet protocol. For precise assessment of detailed requirements, several components were implemented for testing purposes.

From 6 to 8 February 2006 an NTRIP Symposium took place at the “Literaturhaus Frankfurt“. This event was attended by 130 participants from 30 nations. More than 20 talks informed about the fundamentals of communications technology, real-time GNSS networks, current and future application of NTRIP data as well as the up-to-date development status of NTRIP in the 2.0 Version. The presentation concluded with a workshop on the operating mode and application of the NTRIP software developed by BKG.

Since 2006 the additional NTRIP Broadcaster *www.igs-ip.net*. as a supplement to the previous Broadcaster *www.euref-ip.net* is under operation. Real-time data streams from IGS stations are offered on the newly established Broadcaster as well as from other stations outside Europe. Capacities on the previous NTRIP-Caster are released through this measure, which can be used for the provision of real-time data of new EPN stations. Through both casters about 150 real-time data streams are presently available in different data formats.

[1] Georg Weber / Johannes Ihde: Bundesamt für Kartographie und Geodäsie (BKG), Richard Strauss Allee 11, D - 60598 Frankfurt a.M., Germany, Tel. +49 - 69 - 6333 -391/ -206, Fax +49 - 69 - 6333 -425, e-mail georg.weber@bkg.bund.de / johannes.ihde@bkg.bund.de

[2] Matthias Becker, TU Darmstadt, Institut für Physikalische Geodäsie, Petersenstrasse 13, D - 64287 Darmstadt, Germany, Tel. +49 - 6151 - 163109, Fax +49 - 6151 - 164512, e-mail becker@ipg.tu-darmstadt.de

GLONASS

Since GPS week 1300 (December 2004) the weekly GLONASS precise orbit solution of BKG is part of the official IGS combination solution, together with ESA's results of orbit computation, the results obtained by the University of Berne, and results of the "Mission Control Centre", in Moscow (both SLR and microwave solutions). The combined IGS-GLONASS orbits are provided by the "GeoForschungsZentrum Potsdam".

Since April 2006 the GLONASS satellite orbits are computed by means of the new Version 5.0 of the Bernese GPS software. Utilization of the new software is a prerequisite for the fulfilment of international standards in the field of GNSS data analysis, which includes e.g. introduction of the new reference frame ITRF2005 and the correction of absolute instead of relative antenna phase-centre variations. Through the new version the computing time could be reduced by ca. 25 percent given that now possibilities of parallelization of processes are used. The automated processing components now run clearly more stably, whereby it has become possible to perform the daily solutions automatically already during night time and to do only the combination of daily to three-day orbit arcs manually. With the application of the new software version importance was primarily attached to the reproducibility of results as compared with the respective previous version. The IGS performed some important change in the analysis strategy with the beginning of week 1400, e.g., the switch from ITRF2000 to ITRF2005 and from relative antenna phase centre variations (PCVs) to absolute PCVs. These changes were applied to the GLONASS analysis at the same time.

EUREF GNSS Permanent Network

Work on the European Reference Network EPN includes the computation of a BKG solution for the purpose of a sub-network, the combination of the coordinate solutions and the combination of the troposphere signal path delay of all sub-networks of the 16 analysis centres of the EPN. The activities mentioned last are done on a weekly basis. The BKG solution as one of the solutions of the EPN analysis centres is generated in the course of the common analysis of the GREF and EPN stations and comprises altogether approx. 90 stations.

The upgrade to Bernese GPS Software Version 5.0, introduction of ITR2005 and switch to absolute PCVs were the most essential innovation with regard to the combination of coordinate solutions. The new module ADDNEQ2 for the combination of the normal equations requires a change in strategy. Now the coordinates are introduced as observations. Further, first efforts have been started to develop a new scheme for the weighting of the single solutions of the different EPN analysis centres.

The COST Action 716 "Exploitation of ground based GPS for climate and numerical weather prediction application" ceased in spring 2004 after duration of five and a half years with the completion of an extensive final report. As a follow-up project both to this project as well as to other EU projects, as e.g. TOUGH and MAGIC, the project "The EUMETNET GPS Water Vapour Programme" (E-GVAP) was initiated by some of the participating countries within the frame of EUMETNET, which is a conference grouping 20 European national meteorological services. Unfortunately, the Federal Republic of Germany has not joined this project until now. The near real-time solutions computed by BKG can nevertheless still be contributed to the analytical part of the project. The number of stations evaluated by BKG on a regular basis was in the reporting period increased from 80 to ca 120. On the one hand, the new EPN-stations were taken into account, and on the other hand further GREF stations were integrated.

German Permanent GNSS Networks

The GREF national reference network of the BKG has been further extended to an integrated real-time network. This extension consists of replacing the observation stations with combined GPS/GLONASS receivers and implementing the data transmission in real-time. It has been started to create local security networks for the GREF stations with terrestrial measurements. The extension of GREF also includes the combination of the geometric satellite positioning process with dynamic methods of height determination and/or gravity measurements. Therefore, there are also some stations located close to level measuring stations, geophysical observatories or stations of the German gravity reference network.

The geodetic reference network GREF presently comprises 22 real-time GNSS stations. The data of most stations are transferred via DSL Internet connection to the central office in Frankfurt, where they are processed by means of the networking software EuroNet of Euronik. Pseudo-range corrections are computed for virtual stations, evenly distributed over the territory of the Federal Republic, and transmitted over the Internet using the NTRIP protocol. The service includes a comprehensive monitoring and backup concept that guarantees the availability and quality of the corrections, available in the RTCM 2.0 format.

The daily analysis of the GNSS observation data in the post-processing mode has been performed continuously with the Bernese GPS Software Version 5.0. Besides the routine evaluation beginning with GPS week 1400 the networks are computed with absolute antenna phase eccentricities and using the ITRF2005 / IGS05 reference frame. Test evaluations including GLONASS observations and orbits have been carried out and will be continued aiming to include GLONASS in the regular analysis scheme.

SAPOS is the GNSS reference positioning system of the German states, based on a widespread network of more than 250 permanently operated GPS reference stations. That have been determined based on a diagnostic adjustment in a homogenous, standard reference system of the European Terrestrial Reference System 1989 (ETRS89).

SAPOS provides its customers with correction data in three service areas of different accuracies using agreed transfer media, data formats and fees. Real-time networking has been introduced to enhance the reliability and accuracy of the SAPOS HEPS real-time service. It solves the problem of residual errors caused by the influences of ionosphere and troposphere and errors in the orbital data.

For all SAPOS reference stations, a coordinate monitoring in accordance with national standardised principles is being introduced. It consists, on the one hand, of an online-monitoring within the scope of the networking of these stations and, on the other hand, of a monitoring with precise orbital data in post processing for controlling the highly precise coordinates in ETRS89.

A decision was made to install combined GPS – GLONASS receivers at a sufficient number of sites to enable multi GNSS RTK applications in the coming years with the replacement cycle of the equipment. This high quality infrastructure of ground GPS receivers, established for surveying and navigational purposes, is also used for the meteorological community with a small additional effort. GFZ Potsdam uses 218 stations of SAPOS, 10 of BKG, 12 GFZ owned sites installed at synoptic sites of the German Weather Service and 32 others for the NRT monitoring of the vertical integrated water vapour (IWV) in a German network with a precision of about 1 to 3 mm (~5%).

The objective of the central SAPOS agency installed at the State Survey and Geospatial Basic Information Lower Saxony (LGN) in Hannover concerns in particular the provision of SAPOS data for nationally active users. Besides the increasing of the long-term acceptance of SAPOS, the AdV (Arbeitsgemeinschaft der Vermessungsverwaltungen der Länder der Bundesrepublik Deutschland) also promises an increase in the cost efficiency of the SAPOS services of the States installed with high financial expenditure by the member authorities.

The trend, diagnosed for some years, that the traditional, terrestrial marked fixed point fields are becoming less and less important, has been confirmed. Despite the satellite measuring technology, they still cannot be completely dispensed with. Therefore, based on the possibility of providing a major part of the spatial reference via SAPOS in the future, in 2004 the AdV decided on a strategy for a nationally uniform spatial reference of the official surveying and mapping in the Federal Republic of Germany.

Analysis of 1 Hz GPS Observations

The devastating $M_W = 9.3$ Sumatra-Andaman earthquake of 26 December 2004 was so strong that it led even at very distant points of the earth to temporary surface movements which could be recorded in the cm-range. These movements could be monitored not only by means of seismometers, superconducting gravimeters or BKG's ring laser installed at the Fundamental Station Wettzell, but also through differential GPS. For this purpose, GPS observations with a data-recording rate of 1 Hz were evaluated using Bernese software version 5.0. The position of the rover station was determined for each second from doubly differentiated L_3 phase observations after fixing the ambiguities.

For the territory of the Federal Republic of Germany a large number of GREF and SAPOS stations were available to BKG for carrying out this analysis. Owing to the high temporal and spatial resolution as well as to the high accuracy obtained in the evaluation, it was possible to prove the progression of the Love waves – which are surface waves moving away from the seismic focus at a speed of ca 4 km/s – in the east-west direction as well as the resulting surface deformations in the north-south direction (perpendicular to the direction of propagation).

Integration of SAPOS Stations in GREF, EUREF and IGS

To be able to continue securing the official SAPOS coordinates in a homogeneous and permanent manner, the AdV has dealt with the introduction of a different form of monitoring since the beginning of 2006 and on the basis of a superior reference frame. This new reference frame labelled 'DREF-Online' shall primarily be composed of the stations of the GREF permanent network as well as of some selected SAPOS reference stations (SAPOS Core Sites) and serve the monitoring and analysis of wide-area stability. To establish reference to the official coordinates of the SAPOS reference stations the DREF-Online stations are assigned coordinates in the ETRS89 system, with their alignment in the DREF91/SAPOS Diagnosis Adjustment 2002. It is presently still discussed in which concrete form and division of work the monitoring shall be carried out.

Cooperation in Galileo

Within the 6th framework programme of the European Commission a consortium under the guidance of the GeoForschungsZentrum Potsdam develops the Galileo Geodetic Service Provider Prototype (GGSP Prototype). The partners are the Astronomical Institute of the University of Berne, the European Space Agency ESA at Darmstadt, the Institut Géographique National, France, and BKG. The main objective of the project is the development of scientific, technical and organisational principles for the realisation of the Galileo Terrestrial Reference System (GTRS) on the basis of Galileo sensor stations and special IGS stations. Furthermore the development includes a model for performing all work by a service provider for geodetic assurance of the operation of the GALILEO satellite positioning system.

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Satellite Orbit Modelling

K. H. Ilk[1], M. Rothacher[2], J. Dow[3]

General remarks

The continuous and precise observation of satellite orbits by the Global Navigation Satellite Systems (GNSS) enabled the development of alternative Earth system analysis techniques and even new applications in the Earth system research. Innovative sensor types, such as accelerometers, star trackers and improved tracking receivers as well as new observation types such as precise intersatellite range- or range-rate measurements provided the basis for a precise determination of absolute and relative orbits of satellites and satellite pairs, respectively. Very precise kinematic or reduced dynamic orbits derived from these measurements are required to study sea level change and ice cover variations based on the observations of altimetry satellites, atmospheric sounding by GNSS occultation measurements or the detection of mass transports and the mass distribution in the Earth system by a precise determination of the stationary and time variable gravity field. Therefore the development of improved orbit determination strategies was a topic of research during the last four years.

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[1] Karl Heinz Ilk: Institut für Geodäsie und Geoinformation, Universität Bonn, Nussallee 17, D-53115 Bonn, Germany, Tel. +49 - 228 - 732629, Fax +49 - 228 - 733029, e-mail ilk@geod.uni-bonn.de

[2] Markus Rothacher: GeoForschungsZentrum Potsdam (GFZ), Department 1: Geodesy & Remote Sensing, Telegrafenberg, D-14473 Potsdam, Germany, Tel. +49 - 331 - 2881100, Fax +49 - 331 - 2881111, e-mail rothacher@gfz-potsdam.de

[3] John M. Dow: European Space Operations Centre, Orbit and Altitude Div., Robert-Bosch-Str. 5, D-64293 Darmstadt, Germany, Tel. +49 - 6151 - 902272, Fax +49 - 6151 - 902271, e-mail John.Dow@esa.int

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GNSS Based Sounding of the Atmosphere/Ionosphere

J. WICKERT[1], N. JAKOWSKI[2]

Introduction

During the last decade GNSS based techniques for ground and space based atmospheric/ionospheric sounding were established as the forth pillar of the classic geodetic trinity Earth rotation, geo-kinematics and gravity&geoid (RUMMEL, 2003). The atmospheric refraction, error source for the majority of geodetic applications, is used as measurement signal. Atmospheric properties, as, e.g., globally distributed vertical profiles of refractivity, temperature, water vapor and electron density can be derived from space based techniques. Ground based measurements, provided by global and regional networks, allow for the derivation of vertically or along the line-of-sight (slant) integrated water vapor or electron density (Total Electron Content, TEC) content on a global and also regional scale (see, e.g., WICKERT and GENDT, 2006; JAKOWSKI, 2005a,b).

Space based techniques

Within the reporting period fell the begin of the era of a multi-satellite LEO (Low Earth Orbiter) constellation for precise atmospheric sounding on a global scale using the innovative GPS Radio Occultation (GPS RO) technique. In addition to the German CHAMP (CHAllenging Mini-satellite Payload) satellite (e.g., REIGBER et al., 2005; WICKERT et al., 2006a, 2004a), which provides almost continuously data since 2001, data from several additional missions became available in 2006. GPS RO aboard the U.S.-German GRACE-A satellite (Gravity Recovery And Climate Experiment) was continuously activated on May 22, 2006 (BEYERLE et al., 2005; WICKERT et al., 2006b, 2005). The six satellites of the U.S.-Taiwan COSMIC/ Formosat-3 (Constellation Observing System for Meteorology, Ionosphere and Climate) were successfully launched on April 15, 2007 and will provide about 2,500 globally distributed profiles per day (e.g., WICKERT et al., 2007). The European operational weather satellite METOP was launched on Oct. 19, 2006 and the GRAS (GNSS Receiver for Atmospheric Sounding) was switched to occultation mode for the first time on Oct. 27. 40 measurements were recorded during one revolution, each lasting ~100 min.

This LEO configuration (as of April 2007) will be extended soon by the German TerraSAR-X, which is foreseen to be launched in May 2007 with a Russian Dnepr-1 from Baikonur. Several activities in other countries led to the realization of additional occultation missions, as, e.g., OCEANSAT (India), KOMPSAT-5 (South Korea) and TANDEM-X (Germany). The application of GPS RO aboard several satellites multiplies the potential of the innovative atmospheric sounding technique for several applications in atmospheric research, weather forecast and climate change related studies.

A highlight of these applications is the use of GPS RO data to improve global weather forecasts (e.g., HEALY et al., 2007). Hereby a breakthrough was reached. Data from the German CHAMP and U.S.-German GRACE-A satellites (GFZ analyses) were assimilated as the first GPS radio occultation measurements operationally in 2006 to improve global weather forecasts at the U.K. MetOffice, the European Centre for Medium-Range Weather Forecasts (ECMWF) and the Japan Meteorological Agency (JMA). Currently the data are assimilated in parallel with COSMIC/Formosat-3 data.

The CHAMP data set (started in 2001 and covers as of 2007 already 6 years), including analysis results is made available by GFZ for the international scientific community. The data were and are the basis for the preparation of several occultation missions, the improvement of analysis algorithms (e.g. BEYERLE et al., 2006), and are used for several atmospheric investigations. Examples for such investigations are, e.g., climatological studies (FOELSCHE et al., 2005) or characterization of global tropopause (SCHMIDT et al., 2006, 2005, 2004) and gravity wave (DE LA TORRE et al., 2006) properties. The CHAMP data set is also used to derive the global distribution of water vapor (e.g., HEISE et al., 2005a) or to reveal weaknesses of meteorological analyses or radiosonde measurements (e.g., GOBIET et al., 2005; WICKERT, 2004).

GPS RO has also been further developed for monitoring the ionosphere (e.g. JAKOWSKI, 2005a,b). To estimate resolution and accuracy of the electron density profiles from CHAMP under different geophysical conditions, validation work for ionospheric retrievals was continued and supported by the European COST 271 action (e.g. JAKOWSKI et al., 2005b; STOLLE et al., 2004). Comparative studies with ionospheric 3D models such as IRI (JAKOWSKI and TSYBULYA, 2004) and NeQuick (JAKOWSKI et al., 2005c) were made, demonstrating that the RO measurements can effectively be used for validation and/or development of these models. The data may also effectively be applied for tomographic 3D reconstructions of the ionospheric plasma density distribution as shown by STOLLE et al. (2005). Key parameters of the ionospheric profiles such as the scale height can easily be derived from RO data for modeling or reconstruction (STANKOV and JAKOWSKI, 2005, 2006a,b). First approaches were developed for

[1] Jens Wickert: GeoForschungsZentrum Potsdam ,(GFZ), Telegrafenberg, D - 14473 Potsdam, Department 1 – Geodesy and Remote Sensing, Germany; Tel. +49 - 331 - 288-1758, e-mail wickert@gfz-potsdam.de, www.gfz-potsdam.de/atmo

[2] Norbert Jakowski: Deutsches Zentrum für Luft- und Raumfahrt, Institut für Kommunikation und Navigation, Aussenstelle Neustrelitz, Kalkhorstweg 53, D - 17235 Neustrelitz, Germany, Tel. +49 - 3981 - 480-151, e-mail norbert.jakowski@dlr.de

monitoring and evaluating ionospheric irregularities (VIEHWEG et al., 2007; TSYBULYA and JAKOWSKI, 2005).

Beside GPS RO measurements also the GPS navigation data, received by the topside antenna of LEOs provide important information about the geoplasma environment up to GPS orbit heights (HEISE et al., 2005b,c). Combining both types of measurements, the space based data may effectively contribute to monitor the ionospheric space weather conditions (JAKOWSKI et al., 2004a, 2005d).

Ground based sounding

Another highlight of GNSS based remote sensing is the continuous provision of near-real time atmospheric data from a regional German network (currently about 230 stations, including SAPOS), processed at GFZ. The IWV (Integrated Water Vapor) at these stations is provided with accuracy of <1 mm in Near-Real Time (NRT) with average delay of <1 h between measurement and provision of corresponding analyses results (e.g. Gendt et al., 2004). The data are made available within the German DFG-SPP QPF (Quantitative Precipitation Forecast, Intensive observation period) as well as the European activity TOUGH (Targeting Optimal Use of GPS Humidity data for weather prediction), which is continued by E-GVAP (EUMETNET GPS water VApor Programme, within the network of the European Meteorological Services) with institutions of 15 participating countries to investigate the influence and to stimulate the operational use of GPS ground data to improve numerical weather forecasts (e.g. Dick and Soehne, 2005). Herein, the GFZ data represent the major share. Similar NRT activities, contributing to E-GVAP, are performed by BKG, starting from cooperation with Universität der Bundeswehr München (e.g., BECKER et al., 2003), mainly based on EUREF Permanent Network (EPN) stations. The continuous use of these data to improve operational weather forecasts started in September 2006 at MeteoFrance and in early 2007 at the MetOffice (U.K.).

Currently the IWV investigations are extended to the global IGS network. Initial results of GPS derived IWV data (using global analyses from ECMWF and synoptical data for the needed meteorological ground information) from the IGS network ZTD (Zenith Total delay, GFZ analyses) data were presented by Heise et al. (2007). These investigations and the application to future available, consistent GPS derived ZTD long-term data sets (e.g. STEIGENBERGER et al., 2006) will allow for first climatological investigations based on GPS ground data.

Various activities related to ground based meteorology are also performed at the University Karlsruhe (e.g., LUO et al., 2007 or MAYER, 2006). One main focus hereby is the derivation of IWV data in the area of the Antarctic peninsula.

During the reporting period also initial work on the operational derivation and provision of the atmospheric delay along the line-of-sight to the GPS satellites (slant delay) for the German NRT network was performed. These data exhibit higher information content compared to the ZTD. But initial slant delay results (DICK et al., 2007) have shown the necessity for additional effort to improve the slant delay quality at lower elevation angles, which are needed, e.g., for the application of tomographic reconstruction techniques to derive 3D water vapor distributions (e.g., BENDER et al., 2007; BENDER and RAABE, 2007).

Another main focus in the reporting period were investigations regarding the influence of atmospheric mapping functions based on numerical weather prediction models on the GPS parameter estimation (e.g. BOEHM et al., 2007; VEY et al., 2006).

Small GPS ground networks (6 stations) were also used to investigate correlations between the recorded GPS phase data and atmospheric turbulence (SCHÖN and BRUNNER, 2006).

A potential extension of the static ground based networks for GNSS meteorology can be moving platforms such as ships. Initial results from SCHÜLER (2006) indicate that IWV can be derived with accuracy (standard deviation) of 3.9 mm or better in 50% of the experiments and in 25% even better than 2.0 mm. These results are encouraging for future research in this field.

The calibration of water vapor radiometers (WVR) and their use for validation and accuracy improvement of GPS height determination was investigated by HÄFELE et al. (2004a,b). The direct measurement of water vapor content of the atmosphere by means of WVR enables the development of better correction models and the identification of systematic errors in GPS data.

First systematic comparisons of IWV data from the German NRT network with measurements from sun photometers (world wide AERONET) and ECMWF data were performed for 5 stations at Germany (HEISE et al., 2006). The agreement was very good for all stations, but GPS data were on average about 1 mm more wet compared to the photometer data. In general the agreement between GPS and photometer was better than with ECMWF.

Tropospheric studies were also done by VLBI groups (Very Long Baseline Interferometry), e.g. to investigate the effect of different tropospheric mapping functions on the TRF, CRF (Terrestrial and Celestial Reference Frame) and position time-series (TESMER et al., 2006). As the sensitifity of VLBI with respect to the troposphere is the same as for GPS, STEIGENBERGER et al. (2006) extensively compared GPS and VLBI derived timeseries of zenith delays and gradients. KRÜGEL et al. (2006) combined such parameters derived from both techniques.

Ground based ionospheric monitoring using GNSS techniques is well established since more than one decade. In recent years operational monitoring systems have been developed for monitoring TEC of the ionosphere. It has been shown in numerous studies that such information is valuable for studying and mitigating the ionospheric impact on navigation and geodetic measurements (e.g. JAKOWSKI et al., 2004c, d; STANKOV et al., 2006; HOQUE and JAKOWSKI. 2006). To provide GNSS reference network operators with proper ionospheric information, a regular GNSS based ionospheric data service SWACI (Space Weather Application Center – Ionosphere; *http://w3swaci.dlr.de*) was established (JAKOWSKI et al., 2005e).

Careful analysis of GPS data obtained from dense GPS networks brought evidence for detecting earthquake signatures in the ionosphere about 10 minutes after the corresponding Rayleigh wave has passed the region (Jakowski et al., 2006).

GPS altimetry and reflectometry/scatterometry

In analogy and parallel to the atmospheric refraction another error source for the most geodetic applications, multi-path effects, can be effectively used as measurement signal for GPS based altimetry and scatterometry/reflectometry. Initial results at GFZ on the basis of ground based measurements indicate an accuracy of ~2 cm for the monitoring of lake surface height variations (Helm et al., 2006a,b; 2005). GNSS reflection measurements (ground and also space based, see, e.g., Beyerle et al., 2002) are currently regarded as potential data source for various applications in geoscience and atmospheric research. Detailed data analysis can reveal information on ice surface properties (roughness), ice coverage of oceans, sea surface heights, significant wave height and wind speed/direction above sea surfaces. The reflected signals also contain information on the propagated atmosphere/ionosphere (e.g. integrated electron content along the ray paths).

Summary and Outlook

GNSS based atmosphere/ionosphere sounding can be regarded as an established remote sensing technique. It will further benefit from increasing densities of global and regional ground networks and an increasing number of LEO satellites. Further progress with respect to spatial and temporal coverage of the GNSS measurements can be reached by the future use of the signals from GALILEO and GLONASS. The continuation of the current scientific investigations will increase the spectrum and the capability of GNSS based atmospheric/ionospheric remote sensing.

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SAR and Imaging Techniques

R. BAMLER[1], M. EINEDER[1], R. DIETRICH[2]

SAR Systems and Technology

Systems and technologies experienced a remarkable development within the last four years, see (BAMLER et al. 2003). ESA's current SAR earth observation system ASAR is placed on ENVISAT, the successor of ERS-1 and ERS-2. These satellites are the basis for the majority of current research and application topics. In addition, ALOS / PALSAR, a Japanese L-Band SAR, was launched in 2006. The data are currently becoming available to scientists.

At present, further missions are to be realized or planned. TerraSAR-X, a high resolution civilian SAR satellite is to be launched in May 2007. The mission is financed and operated in a public private partnership between DLR and EADS Astrium. DLR is responsible for the processing and the scientific exploitation of the data and EADS / Infoterra holds the rights for commercial use (BUCKREUSS et al. 2003, STANGL et al. 2006). SAR-Lupe, a German high resolution military SAR system, consists of 5 satellites. The first satellite was launched successfully in 2006, more satellites will follow in and after 2007. Furthermore, ESA studied an L-Band satellite mission (TerraSAR-L) for the Earth Watch program. DLR/IMF contributed to the phase B study with definitions for processing systems and products (SCHÄTTLER et al. 2004, BREIT and FRITZ 2005, FRITZ and SCHÄTTLER 2005). While TerraSAR-L is currently on hold, the developed concepts are taken over for the imminent ESA Sentinel-1 missions. TanDEM-X, an interferometric mission based upon TerraSAR-X by adding a second satellite in a close formation flight will be realized in 2009. The goal is to establish global 10 meter resolution DEM with 2 meter vertical accuracy (90%, point to point) that will significantly improve the current SRTM data set with respect to resolution, accuracy, coverage and reliability (MOREIRA et al. 2004, BAMLER et al. 2006/07, GILL and RUNGE 2004).

SAR Interferometry and Related Processing Techniques

Many methodological investigations (MEYER et al. 2006c, BAMLER et al. 2005, FIEDLER et al. 2005, BAMLER and HOLZNER 2004, BARAN et al. 2003, HOLZNER and BAMLER 2002) and practical applications have been performed within the last four years. Radar interferometry is being used since the nineties for the measurement of land topography *(Digital Elevation Models*), see (EINEDER 2005, EINEDER and ADAM 2005, HUBIG et al. 2004, EINEDER 2003, EINEDER and SUCHANDT 2003, RABUS et al. 2003).

Another focus of research and application are *slow land surface deformation processes* (BAMLER et al. 2006, HOOPER et al. 2004, KAMPES and HANSEN 2004, KAMPES 2006, BAMLER 2005). Another field of SAR interferometry is the determination of surface deformation and flow velocities for *ice-covered areas* (HORWATH et al. 2006, SHAROV et al. 2003, WENDT 2005, WENDT et al. 2005).

During the recent years the detection and measurement of rather *fast surface motion phenomena such as ocean currents* (RUNGE et al. 2005) and vehicle speed has been demonstrated (MEYER et al. 2006a, HINZ et al. 2006/07, MEYER et al. 2006b, PALUBINSKAS et al. 2006). In *oceanography*, the measurement of wind and wave parameters from SAR is among of the most established applications (LEHNER 2005, LEHNER et al. 2005, SCHULZ-STELLENFLETH et al. 2006, NIEDERMEIER et al. 2005a, NIEDERMEIER et al. 2005b, RICKLEFS et al. 2005, ROMEISER et al. 2005, SCHNEIDERHAN et al. 2005, SCHULZ-STELLENFLETH and LEHNER 2005, HORSTMANN et al. 2004, SCHULZ-STELLENFLETH and LEHNER 2004, SIEGMUND et al. 2004, WERNER et al. 2004, DANKERT et al. 2003, HORSTMANN et al. 2003).

Application-oriented SAR and Related Subjects

Terrafirma is a GMES (Global Monitoring for Environment and Security) initiative triggered by ESA to monitor ground motion in 25 member states of the EU using the persistent scatterer SAR interferometry technique. DLR is acting as an independent quality control instance and defines quality control procedures for the interferometric processing (ADAM 2006).

Information mining and scene understanding methods aim to search for user defined objects and structures in large archives of image data (PALUBINSKAS and DATCU 2006, DASCHIEL and DATCU 2005a, DASCHIEL and DATCU 2005b, DATCU and SEIDEL 2005, DATCU and DASCHIEL 2005, HEAS and DATCU 2005, MAIRE and DATCU 2005, QUARTULLI and DATCU 2004, DATCU et al. 2003, DATCU and SEIDEL 2003, QUARTULLI and DATCU 2003).

[1] Richard Bamler / Michael Eineder: DLR-Institut für Methodik der Fernerkundung (IMF), D - 82234 Wessling, Germany, Tel. +49 - 815328 - 2673, Fax +49 - 815328 - 1420, e-mail richard.bamler@dlr.de / michael.eineder@dlr

[2] Reinhard Dietrich: Institut für Planetare Geodäsie, Techn.ische Universität Dresden, Mommsenstraße 13, D - 01062 Dresden. Germany, Tel. +49 - 0351 - 463 346 52, Fax +49 - 351 - 463 370 63, e-mail dietrich@ipg.geo.tu-dresden.de

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Applications in Engineering

W. SCHWARZ[1], W. NIEMEIER[2]

Introduction

The period 2003 – 2007 is dominated by two developments: The stronger impact of powerful optical measuring systems like laserscanners and lasertrackers on conceptual developments and their applications in different areas of engineering and the concept of integrating sensors and to use them for more complex tasks like guidance of construction machines and kinematic applications.

These developments imply more sophisticated concepts for data processing, their adequate quality assessment and adopted data analysis tools, where non-parametric approaches have got importance.

Laserscanner and Lasertracker

The strong developments in geometry capture systems with the ability of continuous scanning (Laserscanners) or tracking (Lasertrackers) have initiated various activities for the analysis of these new instruments including quality assessment and calibration routines, development of processing algorithms to achieve results in an almost automatic procedure and finally their application in various fields of engineering.

The actual status of the terrestrial laserscanning technique is given in STAIGER and WUNDERLICH (2006). An overview on actual algorithmic developments and practical applications can be found in the proceedings of the national DVW-Seminars on Terrestrial Laserscanning (BARTH et al. 2005, SCHÄFER and NIEMEIER 2006).

The accuracy in the determination of geometrical structures with the available lasersanners is a very important task. Therefore WEHMANN (2007) is going to set-up a test field for this purpose. Furthermore results of different engineering investigations are presented in KERSTEN et al. (2005), STERNBERG et al. (2005).

HEUNECKE and NIEMEIER (2004a and b) have discussed the potential of these new measuring systems and proposed a change of the paradigma in engineering geodesy, caused by these new developments.

In the future Laserscanners will be set up also for kinematic applications, for example for the monitoring of wind power plants, cf. HESSE et al. (2006), KUTTERER and HESSE (2006).

Positioning of Kinematic Objects

The research focus was on the development of modular low-cost multisensor systems. A Kalman filter based on a non-accelerated circle drive that integrates DGPS, odometers, gyroscope and optical speed and distance sensor was developed. The speciality is the use of a measurement quantity as regulating variable. The filter was used for other sensor combinations, too. The stochastic modelling of coloured GPS measurement noise within the Kalman filter is investigated by EICHHORN (2005). The evaluation of the system and the sensor integration is carried out by methods of sensitivity analysis RAMM (2006), SCHWIEGER (2006), RAMM and SCHWIEGER (2004).

The integration of different sensors (coupling and integration with GPS; INS, Inclinometers) including the georeferencing is the topic of the investigations of NEUNER et al. (2004), KUHLMANN and EICHHORN (2003).

Further developments of the kinematic multi-sensor-systems KiSS and MoSES (GRÄFE et. al. (2004) for the purpose of the surveying of railtracks were pointed out by HEISTER (2007).

A similar multi-sensor-systems will be applied in precision farming, see SIEMS and KUHLMANN (2006), KUHLMANN and SIEMS (2007).

Calibration and Sensor Examination

Reflections for a general check of GPS-receiver-systems are presented in HEISTER (2006). Possibilities for calibration of precision levelling rods will be addressed in HEISTER (2006), HEISTER et al. (2005), HEISTER and SCHAUERTE (2005). A new CCD-based technique for the calibration of levelling rods is published in WASMEIER et al. (2006).

In kinematic applications the most ambitious aim is to determine the time delay between all included sensors when observing moving objects. Because of the high accuracy demands, in some cases it is not possible to generate an even more precise reference for the measurements. Therefore, self-calibration methods, accompanied by concurrent calibration processes, are developed and applied, for example in the angle encoder calibration (DEPENTHAL 2006, 2007).

[1] Willfried Schwarz: Professur Geodäsie und Photogrammetrie, Bauhaus Universität Weimar, D - 99423 Weimar, Germany, Tel. +49 - 3643 - 58 45 30, Fax +49 - 3643 - 58 45 34, e-mail willfried.schwarz@bauing.uni-weimar.de

[2] Wolfgang Niemeier: Institut für Geodäsie und Photogrammetrie, Technische Universität Braunschweig, D - 38108 Braunschweig, Germany, Tel. +49 - 531 - 391 74 73, Fax +49 - 531 - 391 74 99, e-mail w.niemeier@tu-braunschweig.de

The stability of temperature fields in laboratories is important for the quality of the measurements carried out. In ESCHELBACH (2007) some investigations are published.

Analysis Methods and Quality Assessment

To model the behaviour of a bridge in MIIMA and NIEMEIER (2004), concepts of Fuzzy-Process-Modelling and Artificial Neural Networks are successfully applied. The derived model of behaviour concerning the structure has been proved to serve for a prognosis for a limited time span.

The implementation of Neuro-Fuzzy-Techniques for modelling the deformations of a lock is pointed out by BOEHM and KUTTERER (2006).

The automated shape recognition of laser scanned deformable objects is presented in HESSE and KUTTERER (2006). ELING (2006) has developed an approach to setup a complete deformation analysis using laserscanning data.

An introduction in the theory of the uncertainty of measurement is given by HEISTER (2005). The use of an interval-based description of measurement uncertainties due to remaining systematic effects is the topic of SCHÖN and KUTTERER (2006). In NEUMANN and KUTTERER (2007) congruence tests and outlier detection are extended with respect to observation imprecision.

On-Site Recording in Architecture and Cultural Heritage

Research and development were focused on new hardware and software, of which the primary use are on-site recording in achitecture and in cultural heritage. Progress has been made as far as the integration of cameras into reflectorless-measuring motorized total stations is concerned. New measuring-methods have been developed and improvements have been made in the field of monument-documentation and the establishment of sustainable networks in monuments and sites for architectural research and for deformation measurements SCHERER (2004).

The new recording method of phototacheometry has been developed by SCHERER (2006). It combines elements of both tacheometry and photogrammetry: General qualities of geometric primitives are simply defined by tacheometric means, while precise object-describing-points are defined via the intersection of image rays with the tacheometrically pre-defined geometry. An excellent degree of automation, control as well as general work economy are achieved resulting in visualisation and animation of the photorealistic and geometrically correct model in the field.

Modern digital surveying and documentation methods should be adapted for an optimal use in the field of building conservation. An overview about the specific demands on building documentation and an optimized documentation strategy is given by WEFERLING (2005). Deformation measurements at historical buildings determines STERNBERG (2006) with terrestrial laserscanners.

Monitoring of Constructions

The automatic determination of deformations of bridges in real time poses challenges in the measuring techniques and in the analysis methods. In SCHWARZ (2003) first results of investigations were pointed out to determine vertical deformation during loading experimentals using methods of digital close range photogrammetry. In slow-developing processes the vertical deformation will be detected with hydrostatically measurement systems. SCHWARZ (2004) introduces a new method in detecting the water surface without any contact by the signal propagation delay of ultrasonic signals.

With the detection of simulated vibrations the actual state of bridges can be evaluated. Using laserinterferometer it is possible to measure the vertical deformation of bridges with high accuracy (SCHWARZ 2006).

The continuous application of an automated total station with target recognition for long-term monitoring of a bridge is presented in HEINERT and NIEMEIER (2007), emphasising aspects of an unstable instrument support and the detection and elimination of systematic effects in the time series.

Faseroptical sensors are adapted to determine the deformation of buildings. In SCHWARZ (2006) the concept of a faseroptical deflectometer for surveying boreholes is introduced. FOPPE et al. (2006) present an autonomous permanent automatic monitoring system with Robot-Tacheometers. The determination of local deformations of highway bridges is the topic of the publication of SCHÄFER (2006). KUHLMANN (2003) carried out studies to temperature induced deformation of a jointless bridge.

Guidance of Construction Machines

The guidance of construction machines implies great demands on the measuring technique and the ruling algorithms. Due to the individuality of construction sites a toolbox with individual modules is developed, that enables to dispose individual automation systems in a simple way by using its “contained expert knowledge”. The modular system is developed with a tachymeter as sensor and a model truck (scale 1 : 14). On the basis of this simulator investigations regarding control and filter algorithms were carried out by GLÄSER (2005), SCHWIEGER and BEETZ (2007).

The control of the orientation of the traverses in tunnel projects is an urgent task. Up to now gyroscopes are used. In NEUHIERL et al. (2006) a new method is presented using an inertial system for the transfer of the directions.

SU et al. (2006) pointed out research of applications for mobile radio Indoor-GPS.

Integration of Measurement Systems into Construction Processes

Methods to automatically integrate measurement systems into construction processes in automatic or semi-automatic way are investigated by MÖHLENBRING and SCHWIEGER (2006). A special focus is directed on the quality assurance and quality safeguarding by optimal use of measurement procedures and surveying instruments to fulfil quality requirements respectively assembly demands. The research is focussed in the setting out of slab tracks for highspeed railways MÖHLENBRINK (2004).

Aspects to integrate a continuous geodetic monitoring system into a construction task are discussed by NIEMEIER (2006) and the use of real-time geometric displacements is a general steering process for a complex tunnel is outlined.

Industrial Surveying

Although in metrology the working space up to 30 m is called scale metrology, from the geodetic point of view this range is related to "low range". Because there is a gap between industry surveying (dealing with working spaces up to 2 m and coordinate measuring machines) and engineering surveying, solutions for all measuring tasks are worked out up to 30 m with an uncertainty demand of u_{95} = 10 µm/m (2 sigma). Furthermore, there are – more or less – no solutions for surveying of (fast) moving objects. Therefore, the focus of research is to develop methods for trajectory determination of objects moving with velocities up to 5 m/s. Uncertainty demands are up to u_{68} = 40 µm (2 sigma) and time assignment is 1 µs HENNES (2006).

The demands on the accuracies for alignment of particle accelerators are partially extremly high. In ALBERT and SCHWARZ (2004) different methods for the alignment are discussed especially for the linear colliders.

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Navigation

S. SCHÖN[1], B. EISSFELLER[2]

Motivation

During the last years, navigation-related topics such as car navigation and location based services entered into everyday live. Also in geodesy, navigation-related issues become more and more relevant. Especially, the advent of the European satellite navigation system Galileo as well as the availability of high sensitivity and software receivers open new applications and give challenging issues for research. Consequently, navigation is also going to take a larger place in the curricula of the German education in geodesy. KNICKMEYER (2003) gives here a comprehensive introduction for students.

Besides the classical application in platform orientation for aero gravimetry and aero photogrammetry or laser scanning, four outstanding fields of research can be distinguished: GNSS-receiver technology, indoor-positioning and navigation, sensor fusion such as GPS/INS-Integration, as well as applications to kinematic positioning, guidance and control. In the following we summarize the publications in each of the topics.

GNSS Receiver Technology

During the last years, major progresses were made in GNSS receiver technology. Especially the market demands (localisation based systems) and the legal conditions in the US (E 911) have pushed the developments of low cost and high sensitivity chips and receivers. Basic research was carried out to enable signal tracking even in harsh environments and with low signal strengths.

Besides an implementation of the whole acquisition and tracking chain in hardware, all major processing steps can be realised in software (*software receiver*). Due to the increase of processing power, they are now ready for the direct signal processing, cf. HEIN et al. (2006), LÜCK et al. (2005), PANY and EISSFELLER (2005), PANY et al. (2003a,b, 2004a,b, 2005a, 2006), SCHMID et al. (2005), and WON et al. (2006a-c). In software receivers, FFT-techniques can be used for the signal acquisition (SICRAMAZ AYAZ ET AL, 2006) enabling a performance that can be compared to massive parallel correlations. In addition, software receivers offer a large playground to develop new receiver designs and tracking techniques like vector delay lock loops (PANY et al. 2005c, PANY and EISSFELLER, 2006), multi-correlators (PANY et al. 2006b), maximum likelihood estimators (MLE) (WON et al, 2006a,b,c), or algorithms for bit synchronisation (ANGHILERI 2006) or for low sample rates (PANY and EISSFELLER, 2003).

On the other hand, inverting the principle of software receivers, dedicated *GNSS signal simulators* can be developed (e.g. PÓSFAY et al. 2005). WINKEL (2003) implemented an end-to-end simulation to take all relevant features for the performance of GNSS receiver into account, especially non-linearities, stochastic processes and the highly complex boundary conditions generated by the interaction of the signal with the environment. In combination with software receiver, the tracking and positioning performance can be analysed a closed loop tests for different harsh tracking conditions, KANIUTH et al. (2004a,b).

The advent of the European Galileo satellite navigation system and the changes in the signal structure that will be made during the GPS modernisation process like, e.g., using multiplexed binary offset carrier (MBOC) modulation, necessitated and stimulated the development of adequate Galileo test receivers and the investigation of new tracking techniques. AVILA-RODRIGUEZ et al. (2006b) analysed the new optimised spreading modulation. In addition, the integration with GPS was investigated (AVILA-RODRIGUEZ and PANY 2004, AVILA-RODRIGUEZ et al. 2004a-d, HEINRICHS et al. 2004, KANIUTH 2005a,b, Pany et al. 2004b). Besides using GNSS signals in the L-band, IRSIGLER et al. (2004) analysed the benefits for navigation from signals in the C-band.

The tracking process itself may suffer from high dynamics encountered by the receiver in some applications. Here, inertial navigation systems (INS) can be deeply coupled and integrated in the receiver to directly measure the dynamic and the resulting Doppler shifts in order to improve the tracking capabilities, PANY et al. (2005b).

SICRAMAZ AYAZ (2005) analysed differential acquisition methods by using Monte Carlo simulations and DISCHLER (2003) the dynamic error model of GNSS receivers, and SANROMÀ GÜIXENS et al. (2003) a new RTK receiver design.

Indoor-Positioning and Navigation

The new tracking technologies, namely the *high sensitivity receivers* and *software-receivers,* allow a tracking of GNSS signals with low signal strength and thus enable a GNNS-based indoor positioning (EISSFELLER et al. 2005a,b, KANIUTH et al. 2004a). PANY (2006) showed that storing

[1] Steffen Schön: Leibniz Universität Hannover, Institut für Erdmessung, Schneiderberg 50, D-30167 Hannover, Germany, Tel. +49 - 511 - 762-3397, Fax +49 - 511 - 762-4006, e-mail schoen@ife.uni-hannover.de

[2] Bernd Eissfeller: Universität der Bundeswehr München, Institut für Erdmessung und Navigation, Werner-Heisenberg-Weg 39, D-85577 Neubiberg, Germany, Tel. +49 - 89 - 6004-3017, Fax +49 - 89 - 6004-3019, e-mail bernd.eissfeller@unibw.de

the digital GNSS signal instead of the “classical” observations (like code and phase data) allows using and integrating additional information during reprocessing with software receivers in post-processing. This is especially beneficial for situations with large signal obstructions and in high multipath environments. However, various open issues are still related to this topic such as the acquisition problematic in extremely severe conditions (AVILA-RODRIGUEZ et al. 2004e, 2005) and the question of optimal GNSS Signals and codes for the indoor positioning for future GNSS (AVILA-RODRIGUEZ et al. 2006a).

Consequently alternative methods and positioning techniques such as wireless LAN are investigated (TEUBER 2006 a,b, TEUBER and HEIN 2005, EISSFELLER et al. 2004). This method is based on signal strength measurements from the WLAN access points.

GNSS/INS-Integration

For many navigation applications a GNSS-only solution is insufficient. Therefore, different sensors such as inertial navigation systems (INS) can be integrated in and combined with GNSS technique. The theoretical approaches and practical test for different INS GPS combinations were carried out by KREYE et al. 2004, SEIFERT and KLEUSBERG (2003, 2004) or DOROBANTU and GERLACH (2004a,b). Further investigations will be directed to integrate optical odometers.

On the other hand GPS and INS can be combined to determine the gravity field. The specific forces are measured by a high precision strap-down INS and the kinematical accelerations are derived using numerous differential GNSS observations, cf. KREYE et al. (2005). STÜRZE and BOEDECKER (2003) showed RMS differences of 3 mm in the altitude component of the same trajectory using different GPS receivers with different high sampling rates. A kinematic lift was developed to provide ground truth height variations for studying the system behaviour of the receivers. This way, it has been possible, e.g., to demonstrate the spectrum deficiency when sampling at 20 Hz instead of 50 Hz, or to carry out ARMA and system analyses (BOEDECKER and STÜRZE 2006). BOEDECKER 2005 proved that the fusion of attitude information from both multi antennae GPS and fibre optical gyros provide transformation parameters between sensor and navigation frame, long term stability and high value and time resolution.

GERLACH et al. (2005) carried out an INS/GPS car experiment in the German Alps for kinematical gravimetry. During ZUPTs an ordinary Scintrex gravimeter was used in parallel for validation. They estimated the accuracy of IMU, during static periods, of a few mGal.

Pseudolites

Pseudolites are GNSS signal emitters on the ground. They enable to improve the weak satellite geometry (e.g. caused by obstructions) and to strengthen thus the position determination, especially of the height component. Consequently, they play a key role for the development of GNSS-based precise landing systems (BIBERGER 2006). The adequate error model for the pseudolite signal reception, especially on reflecting and conducting surfaces of air planes, are studied by BIBERGER (2006), TEUBER (2004) and BIBERGER et al. (2005, 2003a,b). In the context of approaches and landing different investigations were carried out for ground-based augmented systems (GBAS) (HECKER et al. 2006a,b) as well as for enhanced and synthetic vision (KORN and HECKER 2004a,b, HECKER et al. 2004, 2005) and communications (SCHÄNZER and FEUERLE, 2003)

For the real world tests of Galileo receivers, the German Galileo Test and Development Environment (GATE) in Berchtesgaden and the SeaGate at the Forschungshafen Rostock are dedicated test facilities which are based on pseudolite technology.

Applications to kinematic positioning, guidance and control

Within the project Rudy (**R**egionale **U**nternehmensübergreifende **Dy**namisierung von Fahrplaninformation, Buchung und Betrieb im ÖPNV) a geo data based positioning technique was established for public transport. During the test in Ulm with 4 public busses equipped with GPRS technique and a car navigation system, the benefits of the areawide positioning were shown for the planning of time tables, the light-signal prioritisation, the monitoring of buses and the guidance of vehicles in the case of accident, cf. BETTERMANN (2004a,b), BETTERMANN and KAUFMANN (2004) or SCHOLLMEYER et al. (2004).

Do-iT (**D**aten**o**ptimierung für **i**ntegrierte **T**elematik) is a project to improve the acquisition and prediction of traffic state on and apart from federal motorways. The vehicles’ trajectories are determined with signal strength measurements of mobile phone data (Floating Phone Data, FPD) available within the GSM network, and map aiding algorithms on digital road map, cf. RAMM ET AL (2006) or WILTSCHKO et al. (2006).

SCHÜLER (2005) analysed the high-precision kinematic GPS positioning of buoys from IGS and EUREF networks stations to determine the sea-surface height at the time of cross over of ENVISAT satellite for the calibration of its on-board instruments. BÖDER (2006) integrated INS and GPS for real-time marine and hydrographical applications in order to overcome data gaps in the GPS time series.

BLUMENBACH (2004, 2005) and BLUMENBACH and HENKE (2005) investigated the monitoring and the description of the dynamics of ski jumpers.

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IAG PROJECTS

GGOS: the IAG Project

M. ROTHACHER[1]

The Global Geodetic Observing System (GGOS)

The Global Geodetic Observing System (GGOS) has been established by the International Association of Geodesy (IAG) as an IAG Project in July 2003 at the IUGG General Assembly in Sapporo, Japan. In April 2004 the IAG, represented by GGOS, has become a participating organization of the Group on Earth Observation (GEO) and in May 2006 GGOS was accepted as a member of the Integrated Global Observation Strategy Partnership (IGOS-P). GGOS is thus the geodetic component of the Global Earth Observing System of Systems (GEOSS) that integrates all the major observing systems, i.e., the Global Ocean Observing System (GOOS), the Global Climate Observing System (GCOS), the Global Terrestrial Observing System (GTOS), and GGOS.

After the first years devoted to the definition of the internal organizational structure of GGOS and its relationship with external organizations, it is planned to transform the GGOS Project into a permanent element of the IAG structure at the same level as the IAG Services and IAG Commissions at the IUGG General Assembly 2007 in Perugia.

GGOS is the contribution of geodesy to a global Earth monitoring system. In particular, it provides the metrological basis and the reference systems and frames, which are crucial nowadays for all Earth observing systems. GGOS is built on the IAG Services (IGS, IVS, ILRS, IDS, IERS, IGFS, …) and the products they derive on an operational basis for Earth monitoring making use of a large variety of space- and ground-based geodetic techniques such as Very Long Baseline Interferometry (VLBI), Satellite and Lunar Laser Ranging (SLR/LLR), Global Navigation Satellite Systems (GNSS), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), altimetry, InSAR and gravity satellite missions, gravimetry, etc. All these observation techniques are considered integral parts of GGOS, allowing the monitoring of the Earth's shape and deformation (including water and ice surfaces), the Earth's orientation and rotation and the Earth's gravity field and its temporal variations with an unprecedented accuracy. These quantities are direct evidence of many global processes that have a crucial impact on human society such as earthquakes, volcanism, floods, sea level change, climate change, ground water redistribution, mass balance of the polar ice sheets, etc.

At present, the document "The Global Geodetic Observing System: Meeting the Requirements of a Global Society on a Changing Planet in 2020" is written. It will contain the specifications for GGOS in terms of concepts, conventions, infrastructure and services. This document provides the basis for the further development of GGOS over the next decade and more.

German Activities in the Framework of GGOS

Germany is participating in the activities of GGOS in several ways:

1. Memberships in GGOS (Steering Committee, Science Panel, Working Groups, ...);
2. Satellite missions;
3. National Projects.

1. GGOS Memberships

Germany is very active in the GGOS organization as can be seen from the following memberships in GGOS:

Chair of GGOS	MARKUS ROTHACHER (GFZ)
Steering Committee Members	JOHN DOW (ESOC), HERMANN DREWES (DGFI), CORINNA KRONER (University of Jena), BERND RICHTER (BKG), WOLFGANG SCHLÜTER (BKG), TILO SCHÖNE (GFZ)
Science Panel Member	REINER RUMMEL (TU Munich)
Working Group Chairs	HERMANN DREWES (DGFI), BERND RICHTER (BKG)

2. Satellite Missions

Satellites play an important role in Earth observation, since they allow a homogeneous coverage of the Earth. Germany is leading or heavily involved in the following satellite missions that are of importance to GGOS (launch year in brackets, all financed):

- CHAMP (2000): Gravity field, magnetic field and atmospheric sounding mission (GFZ, DLR, NASA);
- GRACE (2002): Gravity field mission with inter-satellite link (NASA, GFZ, DLR);
- GOCE (2007): Gravity gradiometry mission for a high-resolution static gravity field (ESA);
- TerraSAR-X (2007): SAR interferometry mission (DLR, Astrium, GFZ);

[1] Markus Rothacher: GeoForschungsZentrum Potsdam (GFZ), Department 1: Geodesy & Remote Sensing, Telegrafenberg, D-14473 Potsdam, Germany, Tel: +49-331-2881100, Fax +49-331-2881111, e-mail rothacher@gfz-potsdam.de

- TanDEM-X (2009): in tandem with TerraSAR-X, global high-precision digital elevation models (DLR, Astrium, GFZ);
- SWARM (2009): Magnetic field mission with 3 satellites (ESA);
- EnMAP (2011): Hyperspectral optical mission for environmental monitoring (GFZ, DLR).

3. National Projects

The following large scientific projects are contributing considerably to the goals of GGOS:

BMBF Geotechnologien Program

The Geotechnologien Program "Observing the Earth from Space" is financed by the Federal Ministry of Education and Research (BMBF). Within this framework program several projects of relevance to GGOS were funded. The project "GGOS-D" (D for Deutschland), as an example, is a German contribution to GGOS and has as its goal the homogeneous reprocessing of the data of all major space geodetic techniques and the rigorous combination of the generated time series of solutions (including station coordinates, Earth rotation parameters, Earth gravity field coefficients, quasar coordinates, troposphere parameters, etc.). Other projects are dealing with the processing and interpretation of the data coming from the satellite missions CHAMP, GRACE and in future GOCE (gravity field, magnetic field, atmospheric sounding, ionosphere, ...). See *http://www.geotechnologien.de/*.

BMBF German Indonesian Tsunami Early Warning System (GITEWS)

GITEWS is a project of the German Government at the reconstruction of the tsunami-prone region of the Indian Ocean. It is accomplished by a consortium of nine institutions. The establishment of a Tsunami Early Warning System for the Indian Ocean is based on different kinds of sensor systems, that comprise seismometers, GPS instruments, tide gauges and buoys as well as ocean bottom pressure sensors (see *http://www.gitews.de*).

DFG Priority Research Program "Mass Transport and Mass Distribution in the Earth System"

This program of the Deutsche Forschungsgemeinschaft (DFG) focusses on the mass transport processes in the Earth system and the mass distribution in the Earth. Especially the contributions of the new generation of satellite gravity and altimetry missions to geoscience, i.e., to ocean dynamics, ice mass balance, sea level change, dynamics and structure of the Earth interior, glacial isostatic adjustment, continental hydrology, atmosphere, tides and Earth core motion, and their interactions, are studied (see *http://www.massentransporte.de/index.php*).

DFG Research Unit "Earth Rotation and Global Dynamic Processes"

This research program has been formed to get a better understanding of Earth rotation variations, the coupled global processes and Earth sub-systems involved, and to improve the observation technologies and data processing strategies for the determination of Earth rotation variations, e.g., as indicator of global change (see *http://www.erdrotation.de/*).

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Inter-commission Committees (ICC)

A.

ICC on Theory

Overview and Highlights

B. HECK[1]

After the restructuring of the IAG in 2003 the Inter-Commission Committee on Theory (ICCT) partly fulfills the tasks formerly attributed to IAG Section IV on Geodetic Theory and Methodology. Since in the new IAG structure the more topics-oriented work has been shifted to the commissions, the objective of the ICCT is mainly the "pure" theoretical research on a mathematical and physical basis. In view of the unprecedented high accuracy, resolution and quality of geodetic observing systems and data the ICCT concentrates on the study of new mathematical and physical models which may be used in different commissions. Thus, the ICCT is responsible for stimulating mathematical and physical research motivated by geodetic practice, as a contribution to geodetic science and the foundations of Geodesy. Furthermore, the ICCT provides communication links to Mathematics, Physics and Geophysics and aims at attracting young talents of these branches of science to Geodesy, and serves as a home and platform to mathematically motivated geodesists and to application-oriented mathematicians and physicists. As a matter of fact, there exist close ties to the IAG Commissions.

In the period 2003-2007 the scientific work in the ICCT has been organized in the following sub-structure entities:

Working Groups:

- WG-ICCT1: *Inverse Problems and Global Optimization* (Chair: J. KUSCHE, Germany)
- WG-ICCT2: *Dynamic Theories of Deformation and Gravity Field* (Chair: D. WOLF, Germany)
- WG-ICCT3: *Functional Analysis, Field Theory and Differential Equations* (Chair: J. YU, China)

Inter-Commission Study Groups:

- IC-SG2.5: *Aliasing in Gravity Field Modelling* (joint with Commission 2; chair: C.C. TSCHERNING, Denmark)
- IC-SG2.6 *Multiscale Modelling of the Gravity Field* (joint with Commission 2; chair: W. FREEDEN, Germany)
- IC-SG4.2 *Statistics and Geometry in Mixed Linear Models, with Applications to GPS and InSAR* (joint with commission 4; chair: A. DERMANIS, Greece)

Inter-Commission Working groups:

- IC-WG1: *Quality Measures, Quality Control and Quality Improvement* (joint with Commissions 1 and 2; chair: H. KUTTERER, Germany)
- IC-WG2: *Integrated Theory for Crustal Deformation* (joint with Commissions 1 and 3; chair: K. HEKI, Japan)
- IC-WG3: *Satellite Gravity Theory* (joint with Commissions 1 and 2; chair: N. SNEEUW, Germany)

The strong representation of German scientists in the work of the ICCT can easily be recognized form the nationality of the chair persons and members of these sub-entities.

The scientific work has been documented by publications in peer-reviewed international journals such as Journal of Geodesy, Geophysical Journal International, Journal of Geophysical Research, and others, as well as in national journals and publication series, in particular ZfV (Zeitschrift für Vermessungswesen), AVN (Allgemeine Vermessungs-Nachrichten) and the series published by the German Geodetic commission. Many results have also been presented at international symposia, national meetings and workshops of the working groups. For the ICCT the Joint Assembly of the IAG, IAPSO and IABO "Monitoring and Understanding a Dynamic Planet with Geodetic and Oceanographic Tools", which took place on 22-26 Aug. 2005 in Cairns/Australia, had a strong importance, as well as the 6th Hotine-Marussi Symposium (29 May – 2 June 2006, Wuhan/China); while the former Hotine-Marussi Symposia traditionally had been organized in old Italian cities, the venue was shifted to China in order to attract more young researchers from Far East. Furthermore, the IAG Symposium on Gravity, Geoid and Space Missions – GGSM2004 (30 Aug.- 3 Sept. 2004, Porto/Portugal), the 1st International Symposium of the IGFS (28 Aug. - 1 Sept. 2006, Istanbul/Turkey) and the Commission 1 Symposium on Geodetic Reference Frames GRF2006 (9-13 Oct. 2006, Munich/Germany) have to be mentioned, where significant and numerous contributions by German geodesists related to the ICCT have been made. On the national basis, the series of annual meetings *Geodätische Woche (Geodetic Week)* has been continued (2003 Hamburg, 2004 Stuttgart, 2005 Düsseldorf, 2006 Munich); these workshops, organized in the framework of the annual INTERGEO congress, in particular addressed young researchers and PhD students in Geodesy.

Geodetic theory and methodology is also reflected in text books published by German authors in the period of report: In 2003 G. SEEBER presented the second, completely revised and extended edition of his text book *Satellite Geodesy* (W. de Gruyter, Berlin/New York). An overview about classical wavelet analysis and geodetic applications is provided in the volume *Wavelets in Geodesy and Geodynamics* by W. KELLER (W. de Gruyter, Berlin/New York,

[1] Bernhard Heck: Geodätisches Institut, Universität Karlsruhe, Englerstraße 7, D - 76128 Karlsruhe, Germany, Tel. +49 - 721 - 608 3674, Fax +49 - 721 - 608 68 08, e-mail heck@gik.uni-karlsruhe.de

2004), while W. FREEDEN and V. MICHEL published *Multiscale Potential Theory (With Applications to Geoscience)* in Birkhäuser Verlag, Boston/Basel/Berlin 2004. Furthermore, E. GRAFAREND and F. KRUMM completed the comprehensive textbook on *Map Projections – Cartographic Information Systems* (Springer Verlag, Berlin 2006). Finally, the monograph by A. TEUSCH *Einführung in die Spektral– und Zeitreihenanalyse mit Beispielen aus der Geodäsie (Introduction into Spectral and Time Series Analysis with Examples from Geodesy*, Deutsche Geodätische Kommission, Reihe A, Heft Nr. 120, Munich 2006) should be mentioned.

The following sub-chapters on Physical Aspects of Geodetic Modelling and Relativity, Mathematical Aspects of Geodetic Modelling, and Quality Measures and Control report about the work related to the objectives of the ICCT, which was carried out in Germany in the period 2003 – 2007.

The physical aspects of geodetic modelling have been strongly focused on the deformable Earth; due to the deformability of the Earth the geometry of the Earth's surface and its external gravity field are time-dependent. While formerly the geometrical deformation and the change of the gravity field had been treated as separate phenomena, a unified view has been attempted in the past 4-year period, aiming at dynamic theories of deformation and gravity field as well as at an integrated theory for crustal deformation. Significant advances can also be realized in the theory of the determination of the external gravitational field from recent and new satellite missions such as CHAMP, GRACE and GOCE, for the steady-state part as well as for the time-variable components. With respect to the structure of the ICCT reference is made to WG-ICCT2 and IC-WG2/IC-WG3.

The mathematical aspects of geodetic modelling cover both the deterministic and the stochastic model. In the deterministic part main emphasis has been put on the approximation and representation of the Earth's time-variable gravitational field by harmonic and non-harmonic base functions such as classical and spherical wavelets. These base functions have also been used for other applications such as data compression, the regularization of inverse problems, and the investigation of deformations. Great progress has been achieved in adapting wavelets to various fields of Geodesy; high-performance computing is a necessary prerequisite for the use of these new tools. Deterministic aspects of mathematical modelling have mainly been studied within WG-ICCT1, WG-ICCT3, IC-SG2.5 and IC-SG2.6.

Adjustment theory had been the classical tool for quality analysis in Geodesy. In recent years this field has been strongly extended from stochastic to non-stochastic methods of data evaluation, covering parameter estimation, filtering techniques, hypothesis testing, numerical simulation as well as fuzzy data analysis and neuronal networks. More classical fields are mixed linear models, containing e.g. also integer-valued unknowns with applications to GPS ambiguity solutions and the derivation of displacements from InSAR. It can be stated that the arsenal for the analysis of the quality of geodetic measurements and quality control has been strongly increased. The most recent trends concentrate on a unique view of the complete process from data acquisition to provision of final results, comprising measures for integrity, reliability and precision. Studies related to stochastic and non-stochastic methods of data evaluation have been embedded in the work of IC-SG4.2 and IC-WG1.

Physical Aspects of Geodetic Modelling, Relativity

H. Drewes[1], M. Soffel[2]

Introduction

Physical models are used in geodesy for reducing unwanted (disturbing) effects from the observation data on the one hand, and as simplifications and generalizations of the real Earth for geodetic parameter estimation on the other hand. Geodetic parameters refer not directly to reality but to physical models represented by mathematical approaches. The correctness of the models is therefore a critical issue in all geodetic modelling.

Modern geodetic observations are in general based on precise time measurements. This holds for both the geometric observations, where the travel time of electromagnetic waves (optical or microwaves) is measured to derive distances via speed of light, and the gravimetric observations, where the acceleration of free falling probe masses is determined. The dramatic advancement of geodesy in observation and parameter estimation during the last decades is mainly due to the continuous improvement of the time measurements (Drewes, 2006a, b). The progress of physical models is not always consistent with this development, we meet the challenge of improving them. In the following we report about German contributions to these physical aspects of geodetic modelling in the three fundamental fields of geodesy: geometry (positioning), orientation (rotation), and gravity of the Earth. The basic products of geodesy relate to these fields and have to be generated in a uniform, consistent modelling. This is the principal science rationale of the Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) (Drewes, 2007). The performance enhancement of the geodetic observations based on time measurements requires the strict consideration of relativistic effects. Relativity theory shall therefore be treated as a special issue in this report.

Geodetic modelling of geometry, orientation and gravity of the Earth

Geometry modelling

Most important physical models for determining the geometry of the Earth from geodetic positioning are those of the atmosphere and the oceans. Concerning the vertical component of positioning (heights), the physical ocean surface and the gravity field serve as a reference and have precisely to be modelled.

Kaniuth and Huber (2004) use atmospheric pressure models to estimate the loading effects causing height variations in Europe and compare them with GPS observations. The tidal effect of ocean loading is studied by Zahran et al. (2006). Corresponding height variations are presented by Kaniuth and Vetter (2005) at coastal sites from GPS measurements.

Problems related to physical models in the definition of vertical reference frames are discussed by Heck (2004). Ihde and Sánchez (2005) present an approach to globally unify height systems by uniform physical models of the sea surface and the gravity field of the Earth.

Modelling of the Earth's orientation

Variations of the Earth's orientation in space and Earth's rotation are caused by changes of the angular momentum or torque, respectively. These are generated by mass displacements in the solid Earth, the atmosphere and the hydrosphere including the oceans and continental water storage. They have to be represented by physical models for consideration in geodetic parameter estimation.

The influences of core processes on Earth's rotation parameters are studied by Greiner-Mai et al. (2003). The effect of water storage variations on polar motion is presented by Fernandez et al. (2007). Stuck et al. (2005) model the physical mechanism of atmospheric forces in polar motion, and Thomas et al. (2005) concentrate on the contribution of the oceans. Combined modelling of atmospheric and oceanic effects from coupled physical models is published in a series of papers by Seitz (2004, 2005), Seitz et al. (2004), and Seitz and Schmidt (2005). Marchenko and Schwintzer (2003) combine Earth rotation parameters and the Earth gravity field by a combined parameter estimation.

Gravity field modelling

The physical modelling of the gravity field parameters concentrated in the last years on the use of observation data from the satellite gravity field missions CHAMP and GRACE. A number of papers deals with these issues. A new physical approach of gravity field modelling from these missions using the energy integral from kinematic orbits is presented by Gerlach et al. (2003).

Physical models of the solid Earth include isostatic models presented by Kaban et al. (2004) for the entire lithosphere as well as by Wild and Heck (2005). Wziontek (2003)

[1] Hermann Drewes: Deutsches Geodätisches Forschungsinstitut (DGFI), Alfons-Goppel-Str. 11, D - 80539 München, Germany, Tel. +49 - 89 - 23031-1106, Fax +49 - 89 - 23031 1240, e-mail drewes@dgfi.badw.de

[2] Michael H. Soffel, Institut für Planetare Geodäsie, Technische Universität Dresden, Helmholtzstr. 10, D - 01062 Dresden, Germany, Tel. +49 - 351 - 4633-4200, Fax +49 - 351 - 4633-7019, e-mail michael.soffel@tu-dresden.de

parameterises global density models. The continental hydrosphere is probably the most investigated physical aspect in gravity field modelling from space missions. RAMILLIEN et al. (2004, 2005) present an approach for global time variations from GRACE. HARNISCH and HARNISCH (2006) provide the ground truth values from gravimetric data, and NEUMEYER et al. (2006) combine both terrestrial and space observations with hydrology models.

BOSCH (2005) reports about errors in the shipborne marine gravity representation found from GRACE models. The de-aliasing of short-term atmospheric and oceanic gravity variations from GRACE is published by FLECHTNER et al. (2006).

The atmosphere effects are in principle reduced from the geodetic observations by physical models. An approach for atmoshere pressure reduction from gravimetry is given by NEUMEYER et al. (2004).

The reliability of the regional models of mass variations derived from GRACE data processing is discussed by HORWARTH and DIETRICH (2006), where some errors in the modelling are demonstrated.

Relativity

As far as relativistic aspects in geodetic modelling are concerned work concentrated upon three main topics:

– astronomical reference systems,
– dynamical equations of motion and
– relativity tests.

MÜLLER et al. (2007b) present a comprehensive overview on this subject.

Astronomical reference systems

Of great importance for high precision geodetic modelling is the introduction of two fundamentally different celestial reference systems: the Barycentric Celestial Reference System (BCRS) with coordinate time TCB and the Geocentric Celestial Reference System (GCRS) with TCG as coordinate time. SOFFEL et al. (2003) present a detailed discussion of the BCRS and the GCRS. Here, also the relativistic forces acting on a satellite are discussed. Special aspects of local relativistic reference systems are treated in KLIONER (2004). The problem of representation of the cosmic expansion in the BCRS is treated in KLIONER and SOFFEL (2004), SOFFEL and KLIONER (2004a) and in CARRERA and GIULINI (2006). In these papers it was found that the influence of the Hubble expansion of the universe upon physics in the solar system is completely negligible.

Relativistic equations of motion

The problem of relativistic equations of motion of astronomical bodies has been persued into two different directions. In a series of papers Xu and collaborators (XU et al., 2003, 2005) laid the foundation for a relativistic description of elastic deformable astronomical bodies by means of a displacement field. However, this formalism is extremely complex and the relation with observables, e.g., in the field of Earth's rotation is unclear. Another approach, specially designed for the problem of Earth's rotation, starts with a rigidly rotating multipole formalism that is described in detail in KLIONER et al. (2003). This formalism forms the basis for the present post-Newtonian approach to improve Newtonian nutation series. The problem of a relativistic description of Earth's rotation is discussed in SOFFEL and KLIONER (2004).

Relativistic tests

Geodetic space techniques such as SLR, LLR or VLBI are able to provide tests of relativity, both for Special Relativity and Einstein's theory of gravity. Such tests concern the Lorentz-invariance, Newton's law of gravity (the 5th force, $\dot{G}/G$), various forms of the equivalence principle, the determination of post-Newtonian parameters, the geodetic precession and Lense-Thirring effects (frame dragging due to the rotation of the Earth). MÜLLER et al. (2007b) give an overview over such tests. MÜLLER et al. (2006a, 2006b) and MÜLLER (2006) discuss the use of LLR data for such tests of relativity.

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Mathematical Aspects of Geodetic Modelling

W. KELLER[1], W. FREEDEN[2]

Introduction

Mathematical modelling always reacts to newly available data-types or tries to solve problems in modelling, which have not been treated satisfactory so far. From this background the advances in mathematical modelling were primarily triggered by the new data from the CHAMP and the GRACE mission. These new data types generated a need for

- more efficient methods for data screening and correction,
- higher resolution of the data analysis products, both in space and in time.

Both requirements can be met by the use of wavelets. Therefore, the majority of contributions deals in one or another way with construction and use of wavelets.

Independent on the problem at hand, the enormous amount of data requires the application of high-performance computing. A fair amount of publications is devoted to the parallelization of mathematical models of geodetic problems.

Finally, various new ideas for old problems were presented and numerically investigated.

Classical Wavelet Theory

The origin of wavelet analysis was on the real line and on the plane. It is only a couple of years since the main ideas of the classical wavelet theory were generalized to curved manifolds, especially to the sphere. In geodetic context, classical wavelet theory was mainly used for two purposes:

- outlier detection and elimination,
- data or/and operator compression.

The new gravity field missions provide the user with an enormous amount of data. Therefore, numerically efficient methods for outlier detection and elimination are needed. Here the ability of wavelets for time and scale localization is a useful tool. For the data of the CHAMP mission this problem is treated in GÖTZELMANN et al. (2006). Similar questions for the pre-processing of laser-scanning data are studied in BORKOWSKI and Keller (2006).

Another application of wavelet theory is the compression of data or the compression of operators transforming this data. For different kind of geodetic operators this subject is addressed in KELLER (2004) and in KUROISHI and KELLER (2004). An overview about classical wavelet analysis and geodetic applications is given in KELLER (2004).

Spherical wavelets

Spherical wavelets are base functions, which express both: The scale of a signal-pattern and the place of occurrence of this pattern. This makes them particularly useful for localized modelling of various fields on the sphere. Roughly speaking, in the spherical wavelet modelling two different cases can be distinguished:

- the construction of tailored wavelets,
- the use of wavelets for the space-time evaluation of different fields of geodetic relevance.

Wavelets can be tailored for a big variety of applications. In ABEYRATNE et al. (2003) and FREEDEN and MICHEL (2005) the focus was put on deformation analysis. The paper FREEDEN and MAYER (2003) addresses the construction of smooth harmonic spherical wavelets. If vectorial and tensorial quantities are to be analyzed on the sphere, the corresponding wavelets are developed in FREEDEN and MICHEL (2004), and FREEDEN and MAYER (2006). Wavelets on more complicated surfaces than spheres are constructed in MAYER (2004) and MAYER (2006). Spherical wavelets, which are derived from Bernstein instead of Legendre polynomials, are discussed in FENGLER et al. (2006). One of the deficiencies of spherical wavelets is their lack of orthogonality. But at least bi-orthogonality can be achieved, as it is shown in FREEDEN and SCHREINER (2006).

Among the use of spherical wavelets for the study of geodetic fields, four different targets can be distinguished:

- the deformation field of the Earth,
- the ocean circulation,
- and the time-variable gravity field of the Earth, and
- the issue of de-noising and smoothing of different types of data.

Wavelets are used for the investigation of deformations in the publications MICHEL (2003), MICHEL (2004), FREEDEN and MICHEL (2005a) and KAMMAN and MICHEL (2006). The steady-state ocean circulation was studied by means of wavelets in the papers FREEDEN and MICHEL (2004a), FREEDEN et al. (2005), FEHLINGER et al. (2007) and FENGLER and FREEDEN (2005).

[1] Wolfgang Keller: Geodetic Institute, Universität Stuttgart, Geschwister-Scholl-Str. 24/D, D - 70174 Stuttgart, Germany, Tel. +49 - 711 - 6858 3459, Fax +49 - 711 - 6858 3285, e-mail wolfgang.keller@gis.uni-stuttgart.de

[2] Willi Freeden: AG Geomathematik, Fachbereich Mathematik, Universität Kaiserslautern, Kurt-Schumacher-Str.26, D - 67653 Kaiserslautern, Germany, Tel. +49 - 631 - 205-2852 / -3867, Fax +49 - 631 - 205-4736, e-mail freeden@mathematik.uni-kl.de

De-noising and smoothing makes use of the fact that the noise of a signal is mainly concentrated on the smallest scales of a wavelet representation of the corresponding signal. Therefore, an energy reduction on the smallest scales automatically reduces noise and smoothes the field. The application of this idea is discussed in the publications FREEDEN et al. (2003), FREEDEN and MAIER (2003), HESSE and GUTTING (2003).

The majority of wavelet applications falls in the area of recovery of the time-variable gravity field from the data of the CHAMP and GRACE mission. Since the time variability of the gravity field is not uniform but concentrated on a small number of medium-size regions, wavelets are the adequate tool for such kinds of investigations. A wavelet analysis of CHAMP data was presented in the contributions FREEDEN and MAIER (2003), FREEDEN and MICHEL (2003), MAIER and MAYER (2003), MAYER and MAIER (2003), FENGLER et al. (2004), FENGLER et al. (2004a), FENGLER et al. (2004b), FREEDEN and MICHEL (2004), SCHMIDT et al. (2005) and SCHMIDT et al. (2005a).

Similar studies for the GRACE mission are reported in FENGLER et al. (2007), SCHMIDT et al. (2006), SCHMIDT et al. (2007), MAYER-GÜRR et al. (2006) and MAYER-GÜRR et al. (2007).

Besides the analysis of the gravitational field by wavelets also the magnetic field is investigated with the same tools. Results are published in MAYER and MAIER (2003), MAIER and MAYER (2003) and finally, the CHAMP and GRACE data are also used for the study of the ionosphere SCHMIDT et al. (2007a).

A more exotic application of spherical wavelets is in the field of inverse problems. Also here a couple of publications have to be mentioned: MICHEL (2004), MAYER (2004a), MICHEL (2005) and FENGLER et al. (2006a).

Overviews about the use of spherical wavelets in geosciences are given in FREEDEN and MICHEL (2004c), FREEDEN et al. (2003c) and FREEDEN and SCHREINER (2005).

High-performance computing

The processing of data from the CHAMP and the GRACE mission leads to linear systems of equations with a large number of unknowns and an even much larger number of observation data. A direct solution of theses systems of equation requires very much computation time. The target of parallelization is mainly the distribution of independent parts of the computation on different CPUs of a parallel- or vector computer. Here the publications Austen and Keller (2006), AUSTEN et al (2006), BAUR and KUSCHE (2006) and BAUR et al. (2006) have to be mentioned.

Miscellaneous

Independent on the availability of new data type also older, not satisfyingly solved problems have received attention. Here a certainly incomplete list of those topics is to be mentioned:

- A singularity-free alternative to Sanso's gravity space approach is discussed in AUSTEN and KELLER (2007).
- Another topic is the closed solution of systems of polynomial equations, which occur for example in the trilateration problem. Here, new ideas based on Gröbner bases and the Buchberger algorithm have been discussed in AWANGE and GRAFAREND (2003, 2003a, 2003b, 2003c, 2003d, 2003e, 2003f), AWANGE et al. (2003, 2003a, 2003b, 2003c), AWANGE et al. (2004) and AWANGE et al. (2005, 2005a, 2005b).
- For the processing of laser-scanning data new techniques, close to spline approximation, have been proposed in BORKOSKI and KELLER (2003) and BORKOWSKI and KELLER (2005).
- A comprehensive textbook on map projections was published GRAFAREND and KRUMM (2006) and the special kind of harmonic maps was studied in GRAFAREND (2005).

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Quality Measures and Control
(Stochastic and Non-Stochastic Methods of Data Evaluation)

H. KUTTERER[1], W.-D. SCHUH[2]

Introduction and overview

Talking about quality in geodesy is a very heterogeneous task with many different aspects. As the spectrum of methods in geodetic data analysis covers estimation, filtering, testing, and other techniques it is rather hard to provide a clear and unique picture. In all fields a proper modeling is mandatory. This compilation is dedicated to relevant scientific work in Germany within the period 2003-2007. As there has not been much work which was free of applications the following overview presents both the theoretical aspects and the applications in the field of data processing. Most of the presented methods are based on the theory of probability. Some of them have a different background such as fuzzy theory. Nevertheless, all of them can be considered as statistical methods.

The core item of this report is quality. Without doubt, uncertainty can be identified as the main component of quality in geodesy. However, this point of view is incomplete as today's data shows more features of interest than a pure repeatability of the observed (metric) values. The complete process starting with data acquisition and ending with the provision of defined results has to be considered and studied. For this reason an extended quality modeling will become more and more meaningful. First successful steps into this direction are mentioned at the end.

New developments in parameter estimation

It is well known that for many reasons mathematical models in geodesy are only approximate to some extent. There are various strategies to handle this problem. One of them, the so called Total Least-Squares (TLS) approach can be considered as a regression with errors in the variables. Its most significant aspect is the modeling of errors of the design matrix in adjustment models such as the Gauss-Markov model. These model errors are added to the observation errors. KUPFERER (2005) studies some applications of the TLS approach in geodesy.

In case of singular or only weakly regular adjustment problems regularization strategies are required. Some work was dedicated to the optimal determination of the regularization parameter in Uniform Tykhonov-Phillips regularization (CAI et al., 2004). CAI (2004) considered the statistical inference of the eigenspace components of a symmetric random deformation tensor; see also CAI and GRAFAREND (2007).

A prominent quality issue in the derivation of terrestrial and celestial reference frames is the calculation of meaningful uncertainty measures based on the variance-covariance matrix of the estimated parameters. KUTTERER et al. (2007) study a model which takes both the equality of observation values used at different analysis centers and impact of the individual Operator-Software into account. The present continuation focuses on the provision of consistent estimators for the parameters of the reference frames and of the variance of the unit weight.

Further work has to be mentioned on robust estimation where NEITZEL (2003, 2004) studied a combinatorial approach in order to determine maximal point groups which are consistent with respect to congruence transformations. The well-known Gauss-Helmert model has recently received some new attraction regarding the correct way of treating non-linearities; see, e.g., LENZMANN and LENZMANN (2004) or KUPFERER (2004).

Filtering techniques and stochastic modeling

The work on filtering techniques has covered two main topics: colored noise and decorrelation strategies as well as the treatment of instationary time series. Extension and refinement of the stochastic modeling of space-geodetic techniques are also mentioned in this context.

The great amount of data generated by sensors (e.g., during satellite missions) will allow for a precise modelling of the deterministic and stochastic model. To capture the detailed correlation structures present in the sensor signals, complex stochastic models have to be built. Such models are implemented in an efficient manner by means of digital filters with tailored stop and band-pass regions; see SCHUH (2003). Special hypothesis test strategies are necessary to compare the filtered residuals with white noise behaviour to get objective criteria of the quality of the filter process (SCHUH and KARGOLL, 2004). Also the influence of robust parameter estimation procedures was investigated in this context; see KARGOLL (2005). Unfortunately, the computational costs grow considerably when the filter captures more and more details. The question to be addressed will be, whether the quality of the parameter estimates justifies the use of an exact filter (SCHUH et al., 2007).

[1] Hansjörg Kutterer: Geodätisches Institut, Universität Hannover, Nienburger Straße 1, D - 30167 Hannover, Germany, Tel. +49 - 511 - 762-2461/-2462(Secr.), Fax +49 - 511 - 762-2468, e-mail kutterer@gih.uni-hannover.de

[2] Wolf-Dieter Schuh: Institut für Theoretische Geodäsie, Universität Bonn, Nußallee 17, D - 53115 Bonn, Germany, Tel. +49 - 228 - 73 33 95, Fax +49 - 228 - 733 029, e-mail schuh@theor.geod.uni-bonn.de

Typical time series in engineering geodesy comprise instationary components caused by varying external forces. An extension of standard modeling and analysis techniques has been developed by NEUNER and KUTTERER (2006) and NEUNER (2007). It is based on Wavelet transforms and statistical tests and focuses on irregularities of mean and variance of the time series.

A compilation of filtering and related techniques for applications in geodesy was given by TEUSCH (2004). EICHHORN (2005) developed an adaptive Kalman filter for dynamic structural models and applied it to the modeling of the deformations of a steel cylinder induced by heat flow.

In geometric space-geodetic applications the stochastic models of the observations are typically formulated in a straightforward way. Actually, only diagonal matrices are used for the original observations. In publications such as BISCHOFF et al. (2005, 2006) and HOWIND (2006) a procedure is presented which allows formulating and empirically deriving a stochastic model for GPS observations which is rigorously based on filtering techniques and statistical tests for the identification of homoscedastic sequences in the observation residual time series. SCHÖN and BRUNNER (2006) present a physically meaningful approach for the modeling of correlations of GPS phase observations. TESMER (2004) and TESMER and KUTTERER (2004) used the MINQUE approach for the estimation of variance and covariance components of VLBI data.

Model Misspecification and Hypothesis Testing

Many geodetic testing problems concerning parametric hypotheses may be formulated within the framework of testing the validity of a set of linear constraints imposed to a linear Gauss-Markov model. It is then usually argued that a reasonable test statistic should be based on the ratio of the variance factor estimated from the constraints and the variance factor estimated under the unconstrained Gauss-Markov model. Although this procedure is computationally convenient and intuitively sound, no rigorous attempt has been made yet to establish optimality with respect to its power function. Another shortcoming of current geodetic theory has been so far that no rigorous but convenient approach exists for tackling testing problems concerning, for instance, parameters within the weight matrix.

To address these problems, it was proven in KARGOLL (2007) that under the assumption of normally distributed observation various geodetic standard tests, such as Baarda's or Pope's test for outliers, multivariate significance tests or tests concerning the specification of the a priori variance factor, are uniformly most powerful (UMP) within the class of invariant tests. The main characteristic of an invariant test lies in the fact that its power function exhibits certain symmetries with respect to the parameter domain, which is a reasonable assumption as long as no information about the parameters is available a priori. UMP invariant tests were also shown to be generally equivalent to likelihood ratio tests and Rao's Score tests. The latter have the advantage that they do not require the parameter estimates under the unconstrained model, which is convenient if the constraints set parameter values equal to zero. It was shown that the outlier tests mentioned above, being functions of the residuals of a constrained Gauss-Markov model, are in fact particular cases of Rao's Score test, and that also other standard tests may be easily transformed into that form.

Finally, testing problems concerning parameters within the weight matrix such as autoregressive correlation parameters or overlapping variance components were addressed. It was shown that, although strictly optimal tests do not exist in that case, corresponding tests based on Rao's Score statistic are reasonable and computationally convenient diagnostic tools for deciding whether such parameters are significant or not, without requiring the estimation thereof. The current thesis by KARGOLL (2007) concluded with the derivation of the Jarque-Bera test of normality as another application of Rao's Score test, which is useful to check the validity of the normality assumption presupposed in the aforementioned tests.

Numerical Simulation – Monte Carlo Methods

The Gibbs sampler of the Markov Chain Monte Carlo methods was applied to compute large covariance matrices and to propagate them to the estimated parameters (GUNDLICH et al., 2003). Covariance matrices of quantities obtained by linear and nonlinear transformations of estimated parameters can be directly obtained by this method without determining the covariance matrix of the estimated parameters thus saving a considerable amount of computation time. The Gibbs sampler is well suited for parallel computing so that this algorithm for computing covariance matrices was implemented on a parallel computer (KOCH et al., 2004). The method was applied to determine the maximum degree of harmonic coefficients in a geopotential model by hypothesis tests. Random variates for the harmonic coefficients were nonlinearly transformed to random values of quantities used for the hypothesis tests (KOCH, 2005). The Gibbs sampler was also used for the Bayesian reconstruction of digital three-dimensional images of computer tomography. Since the posterior density function for the intensities of the voxels was intractable, the Gibbs sampler by means of sampling-importance-resampling was applied (KOCH, 2005, 2006, 2007a). A review of the Markov Chain Monte Carlo methods, the Gibbs sampler and the sampling-importance-resampling algorithm can be found in KOCH (2007b).

The approach of GUNDLICH et al. (2003) requires a fully populated normal equation matrix, which is not available in iterative solvers. As a solution to this problem, an alternative way to compute the variance-covariance information by Monte Carlo integration was presented in ALKHATIB and SCHUH (2007). The proposed variance-covariance estimation procedure is flexible and may be integrated into many types of solvers such as sparse solvers, parallel direct solvers or iterative solvers. These algorithms were applied in ALKHATIB (2007) to simulated GOCE data, where Satellite Gravity Gradiometry (SGG) and Satellite-to-Satellite Tracking (SST) data observations are combined for recovering the Earth's gravity field.

In order to find an optimal solution to the unknown parameters of the gravity field model, the reliable weighting factor between SGG and SST must be estimated. In order to overcome the ill-condition of the normal equation system, a positive definite regularization matrix (scaled by unknown regularization parameter) must be added to the combined normal equation system. To select both the optimum weighting factors and the optimum regularization parameter KOCH and KUSCHE (2002) demonstrated the Monte Carlo variance component estimation to be a suitable procedure in large-scaled least-squares problems. This procedure for obtaining the variance components was developed by ALKHATIB (2007) to be integrated into the Preconditioned Conjugate Gradients Multiple Adjustment (PCGMA) algorithm of BOXHAMMER and SCHUH (2006), BOXHAMMER (2006).

Fuzzy Data Analysis

Systematic effects play a key role in the error budget of many geodetic applications. Typically, the arising errors are modeled in terms of random variables and random distributions. If such an approach is chosen, the data analysis can be completely based on the theory of stochastics. As this procedure shows some shortcomings in terms of inconsistency with practical experiences like, e.g., the reduction of systematic effects just by averaging of observations, a thorough discussion of uncertainty measures in geodesy is urgently needed; KUTTERER and SCHÖN (2004) as well as HENNES (2007) discuss some options in this context. In order to overcome some of the inconsistencies, an alternative methodology has been proposed by KUTTERER (2002) which is based on fuzzy data analysis. The use of interval mathematics (SCHÖN, 2003) can be considered as a special case. This approach was already presented in the previous National Report. It has been extended significantly during 2003-2007 in the following way. Fuzzy intervals can be used to model the uncertainty caused by remaining systematic effects in the observations (NEUMANN and KUTTERER, 2006, 2007). The respective uncertainty measures (spread, interval radius) can be quantified based on a sensitivity analysis with respect to some originary influence parameters (SCHÖN, 2003). This has been realized for all relevant terrestrial observations and for GPS phase observations (SCHÖN and KUTTERER, 2005, 2006a, b, 2007). The corresponding mathematical propagation of uncertainty is available; the effects of data processing techniques such as observation averaging or differencing are treated in a consistent way. In case of vector-valued quantities the derived multidimensional uncertainty measures are a special case of polyhedrons (zonotopes); see SCHÖN and KUTTERER (2005). Significant progress was also achieved for statistical hypotheses tests for multidimensional fuzzy test statistics (KUTTERER and NEUMANN, 2007). Ongoing work is on a proper extension of the Kalman filter for fuzzy data.

Soft computing techniques

In case of complex applications such as in global geodynamics or the monitoring of large structures it is typically not possible to describe the considered system or object in sufficient detail by mathematical equations which are physically meaningful (structural models). At least to some part the system's or object's behavior has to be modeled in a more or less descriptive manner using regression or comparable models. In the last years neuro-fuzzy approaches such as ANFIS have shown their ability to compete with other methods just as Artificial Neural Networks (ANN). For the prediction of Earth Orientation parameters results were obtained by ANFIS which are similar to ANN but based on a better computer performance (AKYILMAZ and KUTTERER, 2004, 2005). A further comparison of ANN and fuzzy logic has been published by MIIMA and NIEMEIER (2004a, b). At present, the use of ANFIS in causal input-output models is studied for various modeling purposes (BOEHM and KUTTERER, 2006). In this modeling context SCHWIEGER (2004a, b, 2006) is mentioned who has studied a Monte-Carlo based sensitivity analysis of dynamic models which allows to manifest the input-output relation mathematically, and to identify the dominating variables. It is possible to analyse nonlinear and non-additive relations and models in a quantitatively correct way. The particular application was the motion of vehicles.

Extended modeling of quality

Quality in geodesy is typically restricted to modeling and quantifying the uncertainty of estimated parameters of interest based on the concept of mean quadratic deviations or variances, respectively. From a more general point of view additional features have to be taken into account. WILTSCHKO (2004) presents a quality model for applications of geo-data in telematics which comprises measures for integrity consisting of completeness, consistency and correctness, reliability (in a more general meaning as usual) consisting of availability and up-to-dateness, and precision consisting of metric and semantic precision. It is based on fault-tree analysis and failure mode and effect analysis. This extended process-oriented quality model is formulated in a probabilistic framework and can be subject to optimized data acquisition and processing. It has been applied to advanced driver assistance systems.

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B.

ICC on Planetary Geodesy (ICCPG)

ICC on Planetary Geodesy (ICCPG)

CH. KOCH[1], J. MÜLLER[2]

Introduction

Various space missions are in preparation or have already been launched to minor bodies as comets, planets and their moons. Here, geodetic applications and techniques play an ever increasing role. Most of the missions include cameras for imaging the planetary surface or the atmosphere in different spectral wavelengths. Image processing and photogrammetry provide fundamental technologies and analysis algorithms. Moreover, X-rays are also used for spectroscopic mapping of the geological structures of the bodies.

Recently, laser altimetry is getting more and more important in planetary science. Altimeter observations can be used for generating topographic or geological maps, and, in combination with gravimetric data, for determining the long-wavelength gravity field.

One of the first applications in planetary science was Lunar Laser Ranging (LLR). Observations have continuously been taken since the early 70ies. LLR provides one of the longest, non-interrupted space-geodetic time-series.

Lunar Laser Ranging

Lunar Laser Ranging data analysis allows the determination of many quantities of the Earth-Moon dynamics like the Moon's orbit and gravity field, Earth orientation, or the selenocentric and terrestrial reference frames. Most beneficial is the determination of numerous relativistic parameters like the equivalence principle or the time-variation of the gravitational constant. Lunar Laser Ranging observations of about 36 years have been analysed by KOCH (2005), MÜLLER et al. (2006a; 2006b).

Besides the data analyses, LLR shall also be supported by new German range measurements. Therefore the German Fundamental Station Wettzell will be renewed, so that LLR measurements can be expected in the near future. The contribution of LLR for geodetic applications and its visibility shall further be improved by J. Müller (IfE) who serves as LLR representative in the ILRS Governing Board and as ILRS representative in the Directing Board of the International Earth Rotation and Reference Systems Service (IERS) since 2006. More information on recent achievements of LLR is given in the section on "Space Geodetic Techniques (VLBI, LLR, SLR, DORIS)".

Image processing / photogrammetry / spectroscopy

Most of the results related to 'planetary ' image processing in Germany are related to the HRSC-camera onboard Mars Express. ALBERTZ et al. (2005) discuss the photogrammetric background of this camera. GEHRKE et al. (2003; 2006) present mapping results. GWINNER et al. (2005) and LEHMANN et al. (2005) address the determination of large scale digital terrain model. GIESE et al. (2005) present maps of Phobos, ROATSCH et al. (2006) topographic maps of Saturn's icy moons. KELLER et al. (2005; 2007) describe the OSIRIS camera onboard the Rosetta mission developed for mapping the comet's surface. The camera was also used during the Deep Impact mission to the comet Tempel 1. Further photogrammetric data processing in the planetary context is, e.g., discussed in OBERST et al. (2003) and SCHOLTEN et al. (2004; 2005b). The application of spectroscopy for retrieving geological maps of the bodies' surfaces and their composition is presented, e.g., by BASILEVSKY et al. (2004).

Laser altimetry

Laser altimetry is quite a new field in planetary science. Laser altimeters are adopted, e.g., for the MESSENGER or BepiColombo missions. Laser altimeters can be used in planetary science very well because of the different structure and composition of the planets' atmosphere – compared to that of the Earth. Their atmosphere is less dense for investigations in the generally used wavelength of laser altimeters of 1064 nm. Those observations can be analysed to generate topographic or geological maps and to determine time-dependent variations of the quantities of interest.

A laser altimeter was applied, e.g., onboard the Mars Express mission for mapping the surface topography. Another mission planned for Mercury is the BepiColombo mission (OBERST et al. 2006). From a scientific perspective, laser altimeter data sets provide several additional information for retrieving slopes or reflectivity of the surfaces at the chosen laser wavelengths.

[1] Christian Koch: Max-Planck-Institute for Solar System Research, Max-Planck-Str. 2, 37191 Katlenburg-Lindau, Germany, Tel. +49 - 5556 - 979 - 408, Fax +49 - 5556 - 979 - 240, e-mail koch@mps.mpg.de

[2] Jürgen Müller: Institut für Erdmessung (IfE), Leibniz Universität, Hannover, Schneiderberg 50, 30167 Hannover, Germany, Tel. +49 - 511- 762-3362, Fax +49 - 511 - 762-4006, e-mail mueller@ife.uni-hannover.de

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International Bibliographic Service (IBS)

A. KORTH[1]

The International Bibliographic Service (IBS) is based on the literature database Geodesy, Photogrammetry and Cartography GEOPHOKA, which is maintained by the Federal Agency for Cartography and Geodesy (BKG), Branch Office Leipzig.

The activities concerning this literature database started in the years 1984/85 for tasks of surveying and mapping of the former German Democratic Republic (GDR). At that time, also the Center for International Documentation of Geodesy of the Technical University Dresden, the Central Institute of Physics of the Earth, Potsdam, and two research institutes of geodesy and cartography of former Czechoslovakia participated in the development and use of this database. From 1984 to 1991 the database was further developed with program systems of the Automated Information and Documentation System AIDOS under the operating systems OS/ES and VS 2 on large-capacity computers of an external contractor. In autumn 1991 the data stock existing so far was transferred to the IfAG with new software (Leistungsstarkes Archivierungs- und Recherchesystem = LARS). At mid-year 1997 once more a software change was necessary because of the limited search capabilities of the old system and the large amount of literature entries. Since that time GEOPHOKA is running under MIRES (Modular Information Retrieval System) and is freely accessible via the Internet.

In April 2007 the database comprise about 59.000 literature entries, the annual increase is about 1.500 entries. Thematically, the whole special field is reflected in its complexity. Theoretical bases as well as measuring and evaluation techniques are included. Sources for the database are mainly technical journals and all kinds of publications from home and abroad as well as books and the so-called „grey" (unpublished) literature. For each literature source formal, bibliographic and contents data are stored.

One finds a description of the information service including the input screen and some search instructions via the homepage of the BKG (under the link „Services"). Normally, the database is supplemented each working day by results of the evaluation of special literature that are also available for searching immediately after input. Using the search screen it is possible to search for the various features separately or in combination. The syntax is described in the search instructions. The features are author, title, journal, year, language, descriptors and abstract.

Since September 1997 annually about 6 files with approximately 100 to 200 literature sources are compiled from the database for the IBS. Thematically these sources contain information from the fields Theory of Errors and Compensation Computation; Theoretical and Physical Geodesy; Geodetic Control Networks; Astronomy and Space Research and Geophysics.

These compilations are published at irregular intervals as literature list in the „Journal of Geodesy" as IAG Bibliographic Service.

http://www.iag-aig.org/

[1] Annekathrin Korth: Bundesamt für Kartographie und Geodäsie, Außenstelle Leipzig, Karl-Rothe-Straße 10-14, D-04105 Leipzig, Germany, Tel. +49 - 341 - 5634 320, Fax +49 - 341 - 5634 415, e-mail annekathrin.korth@bkg.bund.de