

**NATIONAL REPORT
OF THE FEDERAL REPUBLIC OF GERMANY
ON THE GEODETIC ACTIVITIES
IN THE YEARS 1999 – 2003**

**XXIII General Assembly
of the International Union for Geodesy and Geophysics (IUGG)
2003 in Sapporo/Japan**

**compiled by
Bernhard Heck, Helmut Hornik and Reinhard Rummel**

München 2003

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in Kommission beim Verlag C. H. Beck**

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Foreword

The XXIII General Assembly of the *International Union of Geodesy and Geophysics (IUGG)* to be held in Sapporo, Japan, from June 30 to July 11, 2003, provides an excellent opportunity for taking a look back to the developments in the various fields of Geodesy and Geophysics within the past four-years period. In the following report a summary and overview of the geodetic activities in the period 1999-2003 in the Federal Republic of Germany will be given.

The report has been organized according to the hitherto existing structure of the International Association for Geodesy (IAG) which has been valid since 1991. According to the IAG by-laws the scientific work is distributed over the five sections covering the main aspects and topics in contemporary geodesy:

- *Section I (Positioning)* concentrated on the positioning aspects in geodesy. It considers high precision horizontal and vertical networks, inertial and kinematic positioning, geodetic astronomy, marine positioning and refraction studies. In the past period, main emphasis has been given to GPS-related subjects (the wide area of modelling for precise GPS positioning, regional permanent arrays, multipath mitigation and atmospheric sensing).
- *Section II (Advanced Space Technology)* deals with the development of space techniques such as microwave and laser tracking, radio-interferometric techniques, satellite altimetry, satellite-to-satellite tracking, and satellite gradiometry. The areas of spaceborne interferometry, spaceborne GNS atmospheric sounding, GPS water level measurements, precise orbit determination and calibration/validation of gravity field missions are described in separate sub-sections.
- *Section III (Determination of the Gravity Field)* is concerned with the measurement and evaluation techniques of terrestrial and airborne gravimetry as well as global and regional gravity field modelling and (non-tidal) gravity variations. Special attention has been given to the validation of digital terrain models, the combination of terrestrial and satellite based gravity data, synthetic modelling of the Earth's figure and gravity field, regional geoid modelling in continental and oceanic regions, and altimetry data processing.
- *Section IV (General Theory and Methodology)* deals with fundamental aspects of the mathematical and physical modelling of geodetic observations as well as stochastic and non-stochastic methods of data evaluation. Special emphasis has been given to the use of wavelets, non-probabilistic assessment in geodetic data analysis, fractal geometry, theory of fundamental height systems, joint inverse gravity modelling, and consistent dynamic theories of deformation and gravity field.
- *Section V (Geodynamics)* covers the area of monitoring and study of time-dependent phenomena (polar motion, Earth rotation, Earth tides, recent crustal motions, gravity, sea surface topography and mean sea level). Specific topics are geodetic effects of non-tidal oceanic processes and fundamental parameters.

With the IUGG General Assembly in Sapporo the structure of the IAG will be changed significantly. Much work and efforts of many colleagues have also been devoted to the preparation and implementation of the new structure within the past four-year period.

The editors of this volume and the German Geodetic Commission acknowledge the work of all our colleagues that have contributed to this report. The financial and logistic support by the Bavarian Academy of Sciences for publishing and printing this volume is highly appreciated.

This report can be found in electronic form on the web-site <http://www.dgfi.badw.de/dgfi/DOC/2003/b312.pdf>. The complete volume can also be received on CD from the Secretary of the German Geodetic Commission (Dipl.-Ing. Helmut Hornik, Deutsche Geodätische Kommission, Marstallplatz 8, D - 80539 München, fax +49 - 89 - 23 031 -283 / -100, tel. +49 - 89 - 23 031 113, e-mail hornik@dgfi.badw.de)

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SECTION I
POSITIONING

Positioning

– Overview and highlights –

J. IHDE¹

Overview

German scientists and institutions contributed to all IAG section I bodies during the period 1999 to 2003. The following report is orientated at the structure of the section I bodies. The structure of Section I in the period 1999-2003, established during the IUGG General Assembly in Birmingham, is similar to that for the previous four-year period, in that it consists of one Commission, one Special Commission and four Special Study Groups (SSG).

Commission X “Global and Regional Geodetic Networks”: The goal of the Commission is to focus on the variety of existing control networks (horizontal or vertical, national or continental, global from space techniques) as well as their connections and evolutions. The Commission has two types of subdivisions: Sub-Commissions and Working Groups:

- a) Sub-Commission for large geographic areas: Europe, North America, South America, Africa, Antarctica, South East Asia and Pacific. The Sub-Commissions deal with all types of networks (horizontal, vertical and three-dimensional), and all related projects which belong to that geographical area.
- b) Working Groups for specific technical topics which would be relevant to the Commission’s activities: WG1 on Datums and Coordinate Systems and WG3 on Worldwide Unification of Vertical Datums. -Such Working Groups are not substitutes for a SSG of the IAG, but rather look at technical and practical problems, in particular by establishing specifications for the countries, and also possibly sponsoring training seminars.

Special Commission 4 “Application of Geodesy to Engineering”: The objectives of the Special Commission is on the one hand to document the body of knowledge in the field of the instrumentation and methodology in Engineering Geodesy which has changed by rapid developments in engineering, microelectronics and the computer sciences. On the other hand the objective is to encourage new developments and to present them in a consistent framework. The Special Commission has 6 Working Groups: Real-Time Mobile Multi-sensor Systems and their Applications in GIS and Mapping, Dynamic Monitoring of Buildings and System Analysis, Monitoring of Local Geodynamic Processes and System Analysis, Geodesy on Large Construction Sites, Pseudolite Application in Engineering Geodesy, Application of Knowledge-Based Systems in Engineering Geodesy.

German scientists were also very active in the Special Study Groups:

- SSG 1.179 “Wide Area Modelling for Precise Satellite Positioning”
- SSG 1.180 “GPS as an Atmospheric Remote Sensing Tool”
- SSG 1.181 “Permanent Regional Arrays”
- SSG 1.182 “Multipath Mitigation”

The Commissions and SSGs have all been very productive during the period 1999-2003, and details of their activity are reported below. In particular, there has substantial activity in the topic of SSG 1.180, where GPS is proving to be of significant importance in a number of atmospheric research and operational applications.

Highlights

Compared to the last period 1995-1999 the projects and works for precise positioning on global and regional scales for the realization of spatial reference systems take more and more the character of services. Positioning is closely linked with national, continental and international services.

The leading German research institutes are considerably integrated into all services of the IAG. The GeoForschungs-Zentrum (GFZ) Potsdam is considerably involved in the IGS, the Bundesamt für Kartographie und Geodäsie (BKG) and University of Bonn contribute to the IVS, the Deutsches Geodätisches Forschungsinstitut (DGFI) Munich contributes to ILRS and ITRS. The TU Munich is extraordinarily active in the sector of products for the combination of spatial techniques that are just being built-up. The IERS Central Office established at BKG in 2001 is operating a data center, which ensures the transfer of the IERS product data.

The satellite observation station Wettzell, jointly operated by the BKG and TU Munich, is one of the six geodetic fundamental observation platforms worldwide. The Transportable Integrated Geodetic Observatory (TIGO) started its work in 2002. BKG operates European wide 45 GPS permanent stations.

Furthermore, recent developments go to real-time and/or near-real time services, where the German systems SAPOS and GREF belong to. The permanent network of the Satellite Positioning Service of the German State Surveying Agencies (SAPOS) was almost completed in the period 1999 to 2003,

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the number of sites being 261 in spring 2003. This network provides DGPS and RTK services for positioning and navigation purposes. The German GPS reference network (GREF) operated by the BKG is gradually improved to a real time GPS/GLONASS network since 2000 combined with absolute gravity measurements. Comparable developments can be observed within the Sub-Commission EUREF of IAG's commission X. In the EUREF group with its Permanent Network (EPN) German institutions contributed to the computation of the ITRF 2000. BKG and the Bayerische Akademie der Wissenschaften (BEK) are two of the 16 EPN local analysis centers. The sub-networks are combined by BKG into the official weekly EPN solution.

At the GFZ group on "Active global and regional networks, including SAPOS"; the number of permanent GPS receivers operated by GFZ Potsdam has steadily increased during the last years and amounts to 54 totally in early 2003. BKG is operating 45 GPS permanent stations in Europe.

During the last four years the activities were significantly enlarged for operational requirements of the satellite missions CHAMP and GRACE. A global high-rate (1 sec), low latency (15 minutes) sensor station network was established in 1999 for the CHAMP/GRACE orbit recovery and for monitoring the neutral atmosphere and the ionosphere. Presently this network comprises 15 stations and the data are available via the CHAMP ISDC at GFZ and in the global IGS data centers.

The GFZ and the Deutsche Wetterdienst (DWD) are participating in the European research cooperation COST-Action 716 "Exploitation of Ground-Based GPS for Climate and Numerical Weather Prediction Applications" which is going to finalize at the end of 2003 and which should lead to a routine use of GPS results for numerical weather prediction.

Various studies focused on permanent network sites characteristics, the GPS data quality monitoring, models for RTK networks in view of ambiguity resolution and parameter representation as well as network design and data dissemination.

During the past four years a considerable amount of research work in investigations of nuisance effects in precise GPS positioning has been carried out in Germany.

Absolute and relative calibration techniques of GPS antennas comprise a wide field of activities. Now it is common understanding that in reference station networks, such as the networks of the IGS and SAPOS, as well as for higher precision surveying tasks, only calibrated antennas should be used. Powerful methods of absolute calibration have been developed in Germany. The comparison of calibration values for a set of different antennas obtained by different groups with different methods show that there is agreement on the level of the PCV-patterns of 1 to 4 mm depending on the antenna type and frequency.

Significant progress has been achieved in ambiguity resolution techniques by a more complete modeling of GPS observations. A powerful procedure uses data from permanent reference stations for an error modelling in real-time. This technique reduces distance dependent errors (orbit, troposphere, ionosphere) and at the same time it reduces the time to fix ambiguities and increases the success rate of ambiguity fixing. In Germany this concept is widely used in SAPOS.

In positioning for close range and engineering applications a highlight in the past four years was the advent of laser-scanning in geodesy by German institutions-. By this innovative technique the geometry of structures will be determined or "captured" by a dense, regular distributed raster of points and not - as is usual in geodesy - by a limited number of representative points. A further advanced instrument set-up lasertrackers were introduced, which allow a continuous positioning or kinematic surveying of targets. In contrast to laserscanning here the laserbeam follows automatically a retroreflective target, which is used as handheld device in touch with a regular surface to determine a dense series of 3D-points as representatives for this surface.

The promising developments at the University of the Federal Armed Forces in Munich in the field of multi-sensor-systems, named KiSS and MoSES, for the determination of the trajectory of land vehicles and/or the geometry of streets or other transportation lines including its surrounding could be continued and applied in practice.

Precise positioning on global and regional scales

J. IHDE¹, H. HABRICH², H. HORNIK³, K. H. PAHLER⁴, W. SCHLÜTER⁵

Introduction

In the period from 1999 to 2003 German institutions have contributed to positioning for global and continental applications employing VLBI, SLR and GPS techniques. The main areas of interests are Europe, South America and Antarctica.

The Fundamental Station Wettzell has continued its operation, the Transportable Integrated Geodetic Observatory TIGO was located 2002 at the site Concepcion in Chile and provides since April 2002 continuous VLBI, SLR and also GPS observations. The geodetic observatory O'Higgins at the Antarctic Peninsula operates now since 10 years.

In the frame of the IAG Sub Commission EUREF German activities contributes to the realization of European spatial and height reference frames for scientific and practical applications by GPS campaigns, GPS permanent observations, levelling and tide gauge observations. In South America and Antarctica the projects SIRGAS, CASA and GPS SCAR were continued.

Fundamentalstations Wettzell and TIGO, Antarctic Station O'Higgins

In the period from 1999 to 2003 German institutions have contributed to positioning for global applications employing VLBI and SLR techniques. In particular the Bundesamt für Kartographie und Geodäsie (BKG) in cooperation with the Forschungseinrichtung Satellitengeodäsie (FESG) on behalf of the Forschungsgruppe Satellitengeodäsie (FGS) have carried out continuously VLBI observations with the 20m radiotelescope of the Fundamentalstation in Wettzell and also SLR observations with the Wettzell Laser Ranging System (WLRs) in order to support the realisation and maintenance of global reference frames as the ICRF and the ITRF and also to generate the related Earth Orientation Parameters. The data contribution as well as the related data handling and the data analysis have been realized via the international services of the IAG namely the International VLBI Service for Geodesy and Astrometry (IVS) and the International Laser Ranging Service (ILRS). At the Station

O'Higgins in the Antarctica periodically VLBI observations were performed during campaigns in the Antarctic spring and summer. Those data were provided via the IVS. In order to improve the International Space Geodetic Network by an additional site on the hemisphere the BKG developed the Transportable Integrated Geodetic Observatory TIGO. After the test period at the Fundamentalstation and introduction of required improvements TIGO was move to the southern hemisphere and located at the site Concepcion in Chile, 600 km south of Santiago de Chile. TIGO provides since April 2002 continuous VLBI, SLR and also GPS observations. The Fundamental station Wettzell, the Antarctic station O'Higgins and TIGO contributes significantly as Fundamental stations to the applications in global positioning. In addition to SLR and VLBI at all three sites GPS data were collected which is described in the section of global GPS permanent sites.

VLBI

In Europe, a program of about six observing sessions per year among the 10 European radio telescopes equipped for geodetic VLBI has been carried out since the late eighties under the coordination of the Geodetic Institute of the University of Bonn. The time series of station coordinates has now reached 10 years or more for most of the stations and provides station velocities with an accuracy of ± 0.3 mm/y in the horizontal and ± 0.9 mm/y in the vertical components (HAAS et al. 2000, CAMPBELL and NOTHNAGEL 2000, CAMPBELL et al. 2002). Moreover, the European VLBI network constitutes a highly precise reference frame which contributes to the accuracy and long term stability of the global ITRF's and the European EUREF systems (CAMPBELL 2000). A comprehensive report on the results of the EU-supported Project has been published recently as a TMR Network Report, available at the European Commission, www.cordis.lu/improving (CAMPBELL, HAAS, NOTHNAGEL 2002).

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EUREF

EUREF is the Sub Commission for Europe of IAG's Commission X on Global and Regional Geodetic Networks. The objective of EUREF is the realization and maintenance of a geocentric European reference frame for geodetic and geodynamical applications, and moreover the determination of transformation parameters for the national networks by the main projects:

- the EUREF Permanent Network (EPN)
- a network of high precision geodetic reference sites determined by various GPS campaigns
- the computation of the vertical network (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 forum where these activities are discussed and decisions are taken is the annual symposium, organized since the EUREF foundation. The last symposia have been attended by more than 120 participants coming from more than 30 member countries in Europe. Current activities are governed by the Technical Working Group (TWG). The results of EUREF are available in the symposia proceedings as well on the EUREF homepage (http://www.euref_iag.org/).

Since the beginning of EUREF, Germany is intensively engaged in this IAG project. The secretariat of the Sub-commission is located at the German Geodetic Commission in Munich. Several German geodesists are members of the TWG. The planning and realization of numerous EUREF campaigns was organized and mostly subsidized by the Federal Agency for Cartography and Geodesy (Bundesamt für Kartographie und Geodäsie – BKG) in Frankfurt a. M. and Leipzig. Numerous colleagues from other countries were guests of the BKG to be trained in the analysis of GPS networks. Moreover, the BKG is leading in EUREF activities concerning the vertical networks such as the development of the UELN, the EUVN, the EVS as well as the newly started ECGN. The BKG is also operating as a data and combination center of the EPN, providing access to observations and analysis results through its server.

In the period 1999 – 2003 the following meetings which were planned and organized by the respective local organizing committees in cooperation with the EUREF Secretariat are to be mentioned: The EUREF Symposia in Tromsø, 22.-24. 6. 2000, in Dubrovnik, 16.-19.5.2001 Ponta Delgada, at the Azores, 5.-7.6.2000 and in Toledo, 4.-6.6.2003, and 9 EUREF TWG meetings.

The proceedings of the EUREF symposia were compiled by the EUREF President and Secretary, the printing was financed by the Bayerische Kommission für die Internationale Erdmessung (BEK) in Munich up to vol. 9 and later by the BKG. In the period since the last IUGG General Assembly, the 5 volumes were edited as publications of the IAG / Section I – Positioning; Subcommission for Europe (EUREF). The documentation is also available on the EUREF homepage.

EUREF GPS campaigns

Results of the following EUREF GPS campaigns have been accepted by EUREF as class "B" (1 cm accuracy at the epoch of observation) in the period 1999 to 2003: Moldavia 1999, SWEREF 1999, Balear 98, Great Britain 2001, Poland 2001, Austria 2002, and Hungary 2002. The following 3 campaigns combined the observations over various years in a kinematical model and were thus candidates to be accepted as class "A" (1 cm accuracy in ETRS89): Croatia campaigns from 1994 – 1996, Slovenian campaigns from 1994 – 1996, and Slovakia campaigns from 1993 – 2001. The station velocities were poorly determined and for that reason the campaigns have been accepted as class B as well.

With a European Spatial Reference Workshop 1999 and the Cartographic Projection Workshop 2000 in Marne-la-Vallée the foundations were laid for the definition of uniform European coordinate reference systems in position and height for the spatial referencing of geodata of the European Commission and for future specifications of products to be delivered to the EC and the promotion of wider use of the system within all member states by appropriate means. These activities are related to the Working Group on Datum and Coordinate Systems of the Commission X. The information system for coordinate reference systems (CRS) is a common initiative of EUREF, EuroGeographics, and BKG (<http://crs.ifag.de>). The CRS information system orientates on the international standard ISO 19111. The Information System contains at present: The descriptions of pan-European Coordinate Reference Systems, the descriptions of national Coordinate Reference Systems of European countries and the descriptions of transformations to European Terrestrial Reference System ETRS89.

UELN95/98, EUVN and DHHN92

BKG is data and computing center of the European height projects. With the project of the United European Levelling Network 1995 (UELN95) EUREF continued the realization of a vertical system in a one-decimeter accuracy level over the continent. In 1999 the data and computing center distributed to the contributing countries the solution UELN95/98. UELN95/98 is computed in geopotential numbers and equivalent in normal heights in relation to the Normaal Amsterdam Peil (NAP).

In 2002 the European Vertical Reference Network (EUVN) project started in 1997 with a GPS campaign simultaneous on 200 points was finalized. EUVN is a static integrated network for GPS, levelling, gravity and sea level observations at tide gauges. BKG was GPS and levelling data and analysis center. The European Combined Geodetic Network (ECGN) starting in 2003 is the continuation of the EUVN in the kinematic mode. The information on the projects of European height reference systems are present made available separately at <http://evrs.leipzig.ifag.de>.

The "German Primary Levelling network 1992 (DHHN 92)" bases of the latest precise levelling was established in each of the old and newly formed German States. The heights were calculated as normal heights with the normal gravity

formula of the Geodetic Reference System 1980 (GRS 80) in the level of the NAP. The heights, which were calculated in the system of the DHHN 92, are named "heights above Normalhöhennull (NHN, level datum of DHHN 92)". Since 1st January 2002 the system of normal heights in the system of the DHHN92 has been completely realized in the newly formed German states. The state of work in the old German states is varying. For about one third of all vertical control points located in Germany heights about NHN are all in already available.

SIRGAS/CASA

A second GPS observation campaign of the "Sistema de Referencia Geocéntrico para América del Sur" (SIRGAS) has been observed in 2000. The number of stations has increased compared to the first campaign in 1995. The objective of SIRGAS has been extended on the one hand by the enlargement of the area of interest to Middle and North America, and on the other hand by the effort to standardize the national height systems. The observations has been reduced and analysed by the Deutsches Geodätisches Forschungsinstitut (DGFI).

GPS Observations from the 1999 und 2000 campaigns of the "Central and South America (CASA)" GFZ projects have been analysed and were used to update the existing solutions.

SCAR GPS campaigns

The GPS campaigns of the Scientific Committee on Antarctic Research (SCAR) between 1995 and 1998 provide a valuable data set which is used to link Antarctica with the ITRF (International Terrestrial Reference Frame), and to gain the first detailed insights into the tectonic behaviour of the Antarctic plate. The Working Group on Geodesy and Geographic Information (SCAR WG-GGI) decided to give the responsibility for the organization, data collection and analysis to Germany.

In order to benefit in an optimum way from the large logistics effort, an independent data analysis by six German groups using four different software packages was carried out. The analysis of the seven different solutions provides valuable insights into the stability and reliability of current evaluation techniques for large GPS networks. The level of agreement of 1 cm for horizontal and of 2 cm for vertical position components is an excellent basis for further geodetic research in Antarctica, for example tide gauge fixing, airborne gravimetric surveys or local calibration of satellite remote sensing techniques. The final set of coordinates forms as well an excellent zero basis for future plate kinematic studies. The obtained station velocities already relate Antarctica to the global plate kinematic scheme, and they provide a more detailed view into the recent tectonic situation of the Antarctic Peninsula. in (DIETRICH et. al. 2000 and 2001).

Geodetic work, together with geological and geophysical investigations, provides an excellent basis for a further discussion of tectonic behaviour in Western Antarctica, in particular in the area of the Bransfield Strait.

The Antarctic GPS reference network is a regional densification part of ITRF 2000.

GLONASS

BKG analyses the tracking data of global permanent GLONASS stations and determines improved GLONASS satellite orbits as well as system differences between GPS and GLONASS. The results contribute to the International GLONASS Service (IGLOS), a pilot project of the IGS.

Geodynamical networks

A regional and a local GPS network for the study of tectonic and anthropogenic ground motion in the Lower Rhenish Embayment has been set up in the early nineties and is being observed annually in a campaign-style mode with GPS. Special care has been placed on the selection of the sites and on antenna calibration. From 1994 onwards the derived site motions have begun to show large subsidence of up to 2.5 cm/y due to groundwater withdrawal in the mining areas and after seven years also small tectonic trends of horizontal extension across the Embayment, as well as uplift in the western Rhenish Massif (CAMPBELL et al. 2002).

References

- ADAM J., DUNKLEY P., MARCEL H. V.D., AUGATH W., GUBLER E., SCHLÜTER W., BOUCHER C., GURTNER W., BRUYNINX C., HORNİK H.: *The European reference system coming of age*; In: International Association of Geodesy Symposia, Vol. 121, Springer, Berlin Heidelberg 2000, p. 47-54
- ADAM J., AUGATH W., BROUWER F., ENGELHARDT G., GURTNER W., HARSSON B. G., IHDE J., INEICHEN D., LANG H., LUTHARDT J., SACHER M., SCHLÜTER W., SPRINGER T., WÖPPELMANN, G.: *Status and development of the European height systems*; In: International Association of Geodesy Symposia; Vol. 121, Springer, Berlin Heidelberg 2000, p. 55-60
- ALTINER Y., BECKER M., DZONOV D., POSTOLOVSKI V., SEEGER H., TODOSOV A.: *The Results of the EUREF-FYROM-1996 GPS Campaign*; Report on the Symposium of the IAG Subcommission for EUREF; held in Bad Neuenahr-Ahrweiler, June 10-13, 1998, EUREF Publication No. 7/1, Mitteilungen des Bundesamtes für Kartographie und Geodäsie, No. 6, Frankfurt/Main, 1999, pp 79-88
- ALTINER Y., COLIC K., GOJCETA B., HABRICH H., LIPEJ B., NEUMAIER M., MARJANOVIC M., MEDIC Z., MISKOVIC D., RASIC L., SEEGER H., SELISKAR A., TAVCAR D.: *Results of a Re-Computation of the EUREF GPS Campaigns in Croatia and Slovenia*; Report on the Symposium of the IAG Subcommission for EUREF; held in Bad Neuenahr-Ahrweiler, June 10-13, 1998, EUREF Publication No. 7/1, Mitteilungen des Bundesamtes für Kartographie und Geodäsie, No. 6, Frankfurt/Main, 1999, pp 59-78
- ALTINER Y., SCHLÜTER W., SEEGER H.: *The Results of the BALKAN'98 GPS Campaigns in Albania, Bosnia and Herzegovina, and in Yugoslavia*; Report on the Symposium of the IAG Subcommission for EUREF, held in Prag, June 1-5, 1999, Bayerische Kommission für die Internationale Erdmessung, Astronomisch-Geodätische Arbeiten, 60, 106 113, München 1999

- ALTINER Y., SCHLÜTER W., SEEGER H.: *The EUREF-98 GPS Campaigns in Albania, Bosnia and Herzegovina, and in Yugoslavia*; In: H. Moritz, D. Medak, B. Pribicevic (eds) Proceedings of the International Workshop on Perspectives of Geodesy in South-East Europe, May 2-6, 2000, Dubrovnik, Croatia, Mitteilungen der geodätischen Institute der Technischen Universität Graz, Folge 89, Graz 2001, pp 29-34
- ANGERMANN D., KLOTZ J., REIGBER C.: *Geodetic datum definition of the SAGA network*; In: International Association of Geodesy Symposia, Vol. 120, Springer, Berlin Heidelberg 2000, p. 122-125
- ANGERMANN D., KLOTZ J., REIGBER C.: *Realization of a terrestrial reference frame for large-scale GPS networks*; In: International Association of Geodesy Symposia, Vol. 121, Berlin Heidelberg 2000, p. 304-309
- ARDALAN A., GRAFAREND E., KAKKURI J.: *National height datum, the Gauss-Listing geoid level value w , 0, and its time variation w , 0, (Baltic Sea Level Project: epochs 1990.8, 1993.8, 1997.4)*; In: Journal of Geodesy, Berlin, Vol. 76, Nr. 1, 2002, p. 1-28
- AUGATH W., ADAM J., BOUCHER C., IHDE J., NIEMEIER W., MIERLO J. v., MOLENDIJK R., SCHMIDT K., WINTER R.: *EVS 2000 – Status and Requirements*; In: Veröff. Bayer. Komm. Int. Erdmess., Bayer. Akad. d. Wiss., Astron.-geod. Arb., München, 2000, H. 61, p. 96-98
- AUGATH W., BROSSMANN M., SCHLÜTER W., SUDAU A., WINTER R.: *NNSAT: Precise Height Supervision of Tide Gauges with GPS*; Wegener Meeting Cadiz, Sept. 2000
- BAUERNFEIND E., KILGER R., KRONSNABL G., SCHATZ R., SCHWARZ W., ZEITLHÖFLER R., ZERNECKE R., BIELMEIER E.: *Station Report of the 20 m Radiotelescope at Wettzell*; Annual Report 2001, IVS Coordinating Center, Febr. 2002
- BECKER M., FRANKE P., WEBER G.: *Die Geodätischen GPS-Referenznetze GREF und EUREF-Permanent*; In: Mitt. d. Bundesamtes Kartographie und Geodäsie, Frankfurt am Main, 1999, Bd. 5, p. 140-153
- BECKER M., REINHART E., NEUMAIER P., SEEGER H., RUS T., GHITAU D., MARCU C., RADULESCU F., ROSCA V.: *German and Romanian activities in the frame of the CERGOP: technical report*; In: Mitt. d. Bundesamtes f. Kartographie und Geodäsie, Frankfurt am Main, 1999, Bd. 12, p. 5-63
- BECKER M., ANGERMANN D., NORDIN S., REIGBER C., REINHART E.: *Das Geschwindigkeitsfeld in Südostasien aus einer kombinierten GPS-Lösung der drei GEODYSSSEA Kampagnen von 1994 bis 1998*; In: Zeitschrift Vermess.-wesen, Stuttgart 125 (2000) 3, p. 74 -80
- BECKER M., ANGERMANN D.: *Untersuchungen zur Genauigkeit und systematischen Effekten in großräumigen GPS-Netzen am Beispiel von GEODYSSSEA*; In: Zeitschrift Vermess.-wesen, Stuttgart 125 (2000) 3, p. 88-95
- BECKER M., FRANKE P., WEBER G., INEICHEN D., MERVART L.: *EUREF contribution to ITRF 2000 and analysis coordinator report for 8/99-6/00*; In: Veröff. Bayer. Komm. Int. Erdmess., Bayer. Akad. d. Wiss., Astron.-geod. Arb., München, 2000, H. 61, p. 31-36
- BECKER M., CAMPBELL J., NOTHNAGEL A., STEINFORTH C.: *Comparison and Combination of Recent European VLBI and GPS-solutions*; Proceedings of the 14th Working Meeting on European VLBI for Geodesy and Astrometry, September 2000, Castel San Pietro, Italy, p. 35-40, Bologna 2000.
- BEHREND D., HAAS R., PINO D., GRADINARSKY L.P., KEIHM S.J., SCHWARZ W., CUCURULL L., RIUS A.: *MM5 derived ZWDs compared to observational results from VLBI, GPS and WVR*; Physics and Chemistry of the Earth, June 14, 2001
- CAMPBELL J., VANDENBERG N.: *Very Long Baseline Interferometry (VLBI) – Subcommission Report*; In: CSTG Bulletin No. 15, IAG Commission VIII on Space Techniques, Section II – Advanced Space Techniques, Progress Report 1998, p. 16-31, Munich 1999.
- CAMPBELL J.: *The significance of the European VLBI network for the concept of EUREF*; Symposium of the IAG Subcommission for Europe (EUREF), held at Tromsø, 22-24 June 2000, Veröff. Bayer. Komm. Für die Internationale Erdmessung, Heft Nr. 61, EUREF-Publication No. 9, p. 187-192, München 2000.
- CAMPBELL J., HAAS R., NOTHNAGEL A.: *The European VLBI Project*; In: N.R. Vandenberg and K.D. Bayer (eds.): IVS 2000 General Meeting Proceedings, NASA/ CP-2000-209893, p. 146-150, 2000.
- CAMPBELL J., NOTHNAGEL A.: *Comparison of European VLBI solutions from different Analysis Centers*; Proceedings of the 14th Working Meeting on European VLBI for Geodesy and Astrometry, September 2000, Castel San Pietro, Italy, p. 3-6, Bologna 2000.
- CAMPBELL J., NOTHNAGEL A.: *European VLBI for crustal dynamics*; Journal of Geodynamics, Vol. 30, p. 321-326, 2000.
- CAMPBELL J., NOTHNAGEL A.: *European VLBI for crustal dynamics*; Journal of Geodynamics, Vol. 30, p. 321-326, 2000.
- CAMPBELL J.: *The European Geodetic VLBI Project – An Overview*; Proc. of the 14th Working Meeting on European VLBI for Geodesy and Astrometry, Castel San Pietro Terme, Italy, September 8-9, p. I-VIII, 2000.
- CAMPBELL J., RICHTER B.: *Towards a stable European vertical velocity reference system using VLBI, GPS and absolute gravity measurements*; Proceedings of the 15th Working Meeting on European VLBI for Geodesy and Astrometry, held in Barcelona, Spain, Sept. 7-8, 2001, D. Behrend, A. Rius, Eds., IEEC-CSIC Barcelona, p. 65-74, 2001
- CAMPBELL J., HAAS R., NOTHNAGEL A. (eds): *Measurement of Vertical Crustal Motion in Europe by VLBI*; TMR-Network Publication, Cat. No. KI-NA-20-084-ENC, ISBN 92-894-0763-8, European Commission, 2002
- CAMPBELL J., KÜMPEL H.-J., FABIAN M., FISCHER D., GÖRRES B., KEYSERS CH. J., LHAMANN K.: *Recent movement pattern of the Lower Rhine Embayment from tilt, gravity and GPS data*; Netherlands Journal of Geosciences / Geologie en Mijnbouw, Vol. 81, No. 2, 223-230, 2002.
- CAMPBELL J., NOTHNAGEL A., VENNEBUSCH M.: *Measuring Crustal Deformation in Europe by High Precision Geodetic VLBI*; Proceedings of the 6th European VLBI Network Symposium, Bonn, 25-28 June 2002, ed. by E. Ros, R.W. Porcas, A.P. Lobanow and J. A. Zensus, Max-Planck-Institut für Radioastronomie, Bonn, p. 5-8, 2002.
- DICK W., RICHTER B.: *IERS annual report 2000*; In: Bundesamt für Kartographie und Geodäsie, Frankfurt am Main, 2001, 152 p.
- DIETRICH R., DACH R., ENGELHARDT G., IHDE J., KORTH W., KUTTERER H., LINDNER K., MAYER M., MENGE F., MILLER H.: *Ergebnisse der SCAR GPS Kampagne: ITRF-Koordinaten und Geschwindigkeiten*; In: Dtsch. Geod. Komm., Reihe B, München 2000, Nr. 310, p. 11-20
- DIETRICH R., DACH R., ENGELHARDT G., IHDE J., KORTH W., KUTTERER H., LINDNER K., MAYER M., MENGE F., MILLER

- H., MÜLLER C., NIEMEIER W., PERLT J., POHL M., SALBACH H., SCHENKE H.-W., SCHÖNE T., SEEGER G., VEIT A., VÖLKSEN C.: *ITRF coordinates and plate velocities from repeated GPS campaigns in Antarctica – an analysis based on different individual solutions*; Journal of Geodesy, 74 (2001), 756 – 766
- DREWES H.: *Realisierung des kinematischen terrestrischen Referenzsystems ohne globale Rotation („no net rotation“)*; In: Mitt. d. Bundesamtes f. Kartographie und Geodäsie, Frankfurt am Main, 1999, Bd. 5, p. 120-125
- DREWES H., TREMEL H., FORTES L. P. S., KANIUTH K., HERNANDEZ J. N., SEEMÜLLER W., HOYER M., PEREIRA K. D., STUBER K., WILDERMANN E.: *Monitoring the continental reference frame in South America*; In: International Association of Geodesy Symposia, Vol. 120, Springer, Berlin Heidelberg 2000, p. 134-137
- EUREF reference frame*: In: Veröff. Bayer. Komm. Int. Erdmess., Bayer. Akademie d. Wiss., Astron.-geod. Arbeiten, München, 1999, H. 60, p. 95-105
- FRÖHLICH H., TENHAEF M., KÖRNER H.: *Geodätische Koordinatentransformation: ein Leitfaden*; In: Sankt Augustin: Selbstverl., 2000, 74 p.
- GEEF D., SPATA M., RUF B., LINDSTROT W.: *Zur Realisierung des Systems ETRS89 in Nordrhein-Westfalen: die Bestimmung des NWREF-Netzes*; In: Nachr. Öffentl. Vermess.-dienst Nordrhein-Westfalen, Bonn 32 (1999) 3, p. 142-155
- GUBLER E., HORNİK H.: *Report on the Symposium of the IAG Subcommission for Europe (EUREF), Reports of the EUREF Technical Working Group. Part I*; In: Verlag d. Bundesamtes für Kartographie und Geodäsie, Frankfurt am Main, 1999, 284 p.
- GUBLER E., HORNİK H.: *Report on the Symposium of the IAG Subcommission for Europe (EUREF), Reports of the EUREF Technical Working Group. Part II*; In: Verlag d. Bundesamtes für Kartographie und Geodäsie, Frankfurt am Main, 1999, 170 p.
- GUBLER E., TORRES A. J., HORNİK H.: *Report on the Symposium of the IAG Subcommission for Europe (EUREF) held in Prague, 2-3 Juni 1999. Report of the EUREF Technical Working Group*; In: Veröff. Bayer. Komm. Int. Erdmess., Bayer. Akad. d. Wiss., Astron.-geod. Arb., München, 1999, H. 60, 276 p.
- HAAS R., GUEGUEN E., SCHERNECK H.-G., NOTHNAGEL A., CAMPBELL J.: *Crustal motion results derived from observations in the European geodetic VLBI network*; Earth Planets Space, Vol. 52 (No. 10), p. 759-764, 2000.
- HASE H., SCHLÜTER W., BÖER A.: *TIGO and its future application for the ITRF*; Proceedings of the International Workshop on Geodetic Measurements by the collocation of Space Techniques on Earth (GEMSTONE) January 25-28, 1999, Koganei, Tokyo/Japan
- HASE H., PETROV L.: *The First Campaign of Observations with the VLBI-Module of TIGO*; Proceedings of the 13th Working Meeting on European VLBI for Geodesy and Astrometry, held at Viechtach, February 12-13, 1999, edited by W. Schlüter and H. Hase, Bundesamt für Kartographie und Geodäsie, Wettzell, 1999
- HASE H.: *Phase Centre Determinations at GPS-Satellites with VLBI*; Proceedings of the 13th Working Meeting on European VLBI for Geodesy and Astrometry, held at Viechtach, February 12-13, 1999, edited by W. Schlüter and H. Hase, Bundesamt für Kartographie und Geodäsie, Wettzell, 1999
- HASE H.: *Globale Bezugssysteme und TIGO*; DFG Rundgespräch "Bezugssysteme", Höllenstein, 30. April 1998, Mitteilung des BKG, Band 5, 1999
- HASE H.: *Theorie und Praxis globaler Bezugssysteme*; In: Mitt. d. Bundesamtes für Kartographie und Geodäsie, Frankfurt am Main, 1999, 178 p.
- HASE H.: *Transportable Integrated Geodetic Observatory*; IVS Annual Report 1999, p. 110-115, NASA/TP-1999-209243, Sept. 1999
- HASE H.: *Transportable Integrated Geodetic Observatory*; IVS Annual Report 2000
- HASE H.: *New method for the selection of additional sites for the homogenisation of an inhomogeneous point distribution*; In: International Association of Geodesy Symposia, Vol. 120, Springer, Berlin Heidelberg 2000, p. 180-183
- HASE H., BÖER A., RIEPL S., SCHLÜTER W.: *Transportable Integrated Geodetic Observatory (TIGO)*; IVS-GM-Proceedings, Kötzing, Febr. 2000
- HASE H., BÖER A., RIEPL S., SCHLÜTER W.: *TIGO – Ein bedeutender Beitrag der FGS zur Verbesserung globaler Bezugssysteme*; Begutachtung FGS, Kötzing, 28.-30.06.2000
- HASE H., BÖER A., RIEPL S., SCHLÜTER W., CECIONI A.: *TIGO – Transportable Integrated Geodetic Observatory*; VI Congreso Intern. de Ciencias de la Tierra, Santiago de Chile, Aug. 7-11, 2000
- HASE H., BÖER A., RIEPL S., CARVACHO E., CECIONI A.: *Status of the TIGO-Project*; IVS Annual Report 2001
- HASE H., BÖER A., RIEPL S., SCHLÜTER W., CECIONI A., BATAILLE K., AMTHAUER E., BARADIT E., NARVÁEZ A., CIFUENTES O.: *The TIGO-Project*; ASP Conference Series; Gyeong-ju Korea 2003
- HOWIND J., KUTTERER H., HECK B.: *Impact of temporal correlations on GPS-derived relative point positions*; Journal of Geodesy, 73 (1999), p. 246-258.
- HOYER M., WILDERMANN, E.: *Drei Dekaden satellitengestützter Ortsbestimmung in Venezuela*; In: Wiss. Arb. Fachricht. Vermess.-wesen Univ. Hannover, 2001, Nr. 239, p. 55-62
- HUGENTOBLER U., GURTNER W.: *The Moldavia EUREF Campaign 99*; Report on the Symposium of the IAG subcommission for Europe (EUREF) in Tromsø, 22-24 June 2000, Verlag der Bayerischen Akademie der Wissenschaften, München 2000
- IAG / Section I – Positioning: Subcommission for Europe (EUREF): Publication No. 8: TORRES J., HORNİK H. (eds.): *Report on the Symposium of the IAG Subcommission for Europe (EUREF)*; held in Prague, 2–5 June 1999 / Reports of the EUREF Technical Working Group. München 1999; In: Mitteilungen des Bundesamtes für Kartographie und Geodäsie; 276 p.
- IAG / Section I – Positioning: Subcommission for Europe (EUREF): Publication No. 9: GUBLER E., TORRES J., HORNİK H. (eds.): *Report on the Symposium of the IAG Subcommission for Europe (EUREF)*; held in Tromsø, 22-24 June 2000 / Reports of the EUREF Technical Working Group, München 2000; In: Mitteilungen des Bundesamtes für Kartographie und Geodäsie; 276 p.
- IAG / Section I – Positioning: Subcommission for Europe (EUREF): Publication No. 10: TORRES J., HORNİK H. (eds.): *Report on the Symposium of the IAG Subcommission for Europe (EUREF)*; held in Dubrovnik 16-18 May 2001 / Reports of the EUREF Technical Working Group. Frankfurt a.M. 2002, In: Mitteilungen des Bundesamtes für Kartographie und Geodäsie; 332 p.

- IAG / Section I – Positioning: Subcommission for Europe (EUREF): Publication No. 11: IHDE J., SACHER M. (eds.): *EUVN_Final Documentation*; In: Mitteilungen des Bundesamtes für Kartographie und Geodäsie; Frankfurt a.M. 2002; part I, 91 p., part II, 235 p.
- IAG / Section I – Positioning: Subcommission for Europe (EUREF): Publication No. 12: TORRES J., HORNIK H. (eds.): *Report on the Symposium of the IAG Subcommission for Europe (EUREF)*; held in Ponta Delgada, Azores, 5-7 June 2002 / Reports of the EUREF Technical Working Group; Frankfurt a.M. 2003, in preparation.
- IHDE J., ADAM J., GURTNER W., HARSSON B. G., SCHLÜTER W., WÖPPELMANN G.: *The concept of the European Vertical GPS Reference Network (EUVN)*; In: Report on the Symposium of the IAG Subcommission for Europe (EUREF) held in Bad-Neuenahr-Ahrweiler, June 10-13, 1998, Publication No. 7, Volume II, Frankfurt am Main, 1999, p. 11-22
- IHDE J., ADAM J., GURTNER W., HARSSON B. G., SCHLÜTER W., WÖPPELMANN G.: *Status report of the EUVN project*; In: Veröff. Bayer. Komm. Int. Erdmess., Bayer. Akad. d. Wiss., Astron.-geod. Arb., München, 1999, H. 60, p. 72-79
- IHDE J., SCHLÜTER W., ADAM J., GURTNER W., HARSSON B. G., WÖPPELMANN G.: *Der Beitrag des European Vertical Reference Network (EUVN) zu einem einheitlichen europäischen Höhensystem*; In: Schriftenreihe / Dtsch. Verein f. Vermess.-wesen, Stuttgart, 1999, Bd. 35, p. 120-137
- IHDE J., AUGATH W.: *The Vertical Reference System for Europe*; In: Veröff. Bayer. Komm. Int. Erdmess., Bayer. Akad. d. Wiss., Astron.-geod. Arb., München, 2000, H. 61, p. 99-110
- IHDE J., ADAM J., GURTNER W., HARSSON B. G., SACHER M., SCHLÜTER W., WÖPPELMANN G.: *The height solution of the European Vertical Reference Network (EUVN)*; In: Veröff. Bayer. Komm. Int. Erdmess., Bayer. Akad. d. Wiss., Astron.-geod. Arb., München, 2000, H. 61, p. 132-145
- IHDE J., BOUCHER C., DUNKLEY P., FARRELL B., GUBLER E., LUTHARDT J., TORRES A. J.: *European spatial reference systems – frame for geoinformation systems*; In: Veröff. Bayer. Komm. Int. Erdmess., Bayer. Akad. d. Wiss., Astron.-geod. Arb., München, 2000, H. 61, p. 198-205
- IHDE J., AUGATH W., SACHER M.: *The Vertical Reference System for Europe*; In: International Association of Geodesy Symposia; Vol. 124, Springer, Berlin Heidelberg 2002, p. 345-350
- IHDE J., AUGATH W.: *The European Vertical Reference System (EVRS), Its relation to a World Height System and to the ITRS*; In: International Association of Geodesy Symposia; Vol. 125, Springer, Berlin Heidelberg 2002, p. 78-83
- IHDE J.: *Status report: Geodesy relevant standardisation activities in the frame of ISO TC 211 Geographic Information*; In: Journal of Geodesy, Berlin Vol. 75, Nr. 11, 2001, p. 630-631
- IHDE J., ADAM J., GUBLER E., HARSSON B. G., LUTHARDT J., TORRES, J. A.: *European coordinate reference systems*; In: Mitt. Bundesamtes f. Kartographie und Geodäsie, Frankfurt am Main, 2002, Bd. 23, p. 162-170
- IHDE J., PAHLER K.-H., SCHLÜTER W., WEBER G.: *National Report of Germany to EUREF 2001*; In: Mitt. d. Bundesamtes f. Kartographie und Geodäsie, Frankfurt am Main, 2002, Bd. 23, p. 227-229
- IHDE J., PAHLER K.-H., SACHER M., WEBER G.: *National Report of Germany to EUREF 2002*; In: Mitt. d. Bundesamtes f. Kartographie und Geodäsie, Frankfurt am Main, 2003, in preparation
- ILK K.-H.: *Bericht über die Geodätische Woche 2001 in Köln vom 18.-21. September 2001*; In: Zeitschrift Geod., Geoinf. Landmanag., Augsburg 127 (2002) 2, p. 124-128
- INEICHEN D., IHDE J., GURTNER W., SPRINGER T., ENGELHARDT G., LUTHARDT J.: *EUVN 97 combined GPS solution*; In: Report on the Symposium of the IAG Subcommission for Europe (EUREF), Frankfurt am Main, 1999, p. 23-46
- IRSEN W., SPATA M.: *ETRS89 – European Terrestrial Reference System*; In: Nachr. Öffentl. Vermess.-dienst Nordrhein-Westfalen, Bonn 32 (1999) 3, p. 135-141
- JÄGER R., SCHNEID S.: *Online and postprocessed GPS-heighting based on the concept of a Digital Height Reference Surface (DFHRS)*; In: Mitt. d. Bundesamtes f. Kartographie und Geodäsie, Frankfurt am Main, 2002, Bd. 23, p. 281-286
- JAHN C.-H.: *Das DARA-Projekt HPPS II: Ziele und Ergebnisse*; In: Schriftenreihe Dtsch. Verein f. Vermess.-wesen, Stuttgart 1999, Bd. 35, p. 222-235
- JIVALL L., LIDBERG M.: *SWEREF 99 – an Updated EUREF Realisation for Sweden*; Report on the Symposium of the IAG Subcommission for Europe (EUREF) in Tromso, 22-24 June 2000, Verlag der Bayerischen Akademie der Wissenschaften, München 2000
- KANIUTH K., KLEUREN D., TREMEL H., SCHLÜTER W.: *Elevations-abhängige Phasenzentrumsvariationen geodätischer GPS-Antennen*; ZfV, Zeitschrift für Vermessungswesen, Oktober 1998
- KELM R.: *Datumsoptimale Datenverarbeitung in der Netzausgleichung*; In: Schriftenreihe / Studiengang Geodäsie und Geoinformation Univ. d. Bundeswehr München, Neubiberg, 2000, H. 60-1, p. 167-179
- KILGER R., BAUERNFEIND E., KRONSCHNABL G., SCHATZ R., SCHWARZ W., ZEITLHÖFLER R., ZERNECKE R.: *Station Report of the 20m Radiotelescope at Wettzell*; IVS-Annual Report 2000
- KILLET C.: *Einführung eines neuen geodätischen Bezugssystems und die Bereitstellung geeigneter Transformationssoftware*; In: Allg. Vermess.-nachr., Heidelberg 106 (1999) 1, p. 18-20
- KRONSCHNABL G., REINHOLD A., SCHWARZ W., WOJZIAK R.: *Geodetic Observatory O'Higgins – BKG's IVS Network Station in Antarctica in 2001*; Annual Report 2001, IVS Coordinating Center, Febr. 2002
- LIEBSCH G.: *IAG International Symposium on Vertical Reference Systems, 2001, Cartagena, Kolumbien*; In: Zeitschrift Vermess.-wesen, Stuttgart 136 (2001) 4, p. 234-235
- LINDNER K., MAYER M., HECK B., KUTTERER H.: *Das geodätische Referenznetz Antarktis*; Proc. X. Int. Geodätische Woche, Obergurgl/Österreich 1999. Univ. Innsbruck, Inst. für Geodäsie, Institutsmitteilungen Heft 18, 1999, 103-109.
- MARJANOVIC M., BACIC Z.: *Computation of the Solution of EUREF GPS Campaigns 1994-1996 in the Republic of Croatia*; Report on the Symposium of the IAG subcommission for Europe (EUREF) in Dubrovnik, 16-18 May 2001, EUREF Publication No. 10, Mitteilungen des Bundesamtes für Kartographie und Geodäsie Band 23, Frankfurt am Main
- MAYER M., LINDNER K., KUTTERER H., HECK B.: *Eine Strategie zur Ermittlung hochgenauer Koordinaten und Bewegungsraten im ITRF-96 unter Verwendung der Berner Software*. In: Dietrich R. (Hrsg.): Deutsche Beiträge zu GPS-Kampagnen des Scientific Committee on Antarctic

- Research (SCAR) 1995-1998. DGK B 310, München 2000, p. 59 – 68
- MAYER M.: *Bezugssysteme in der Satellitenvermessung*; In: GPS-Trends und Realtime-Anwendungen: Beitr. 52; Stuttgart, 2001, Bd. 41, p. 47-69
- MENGE F., VÖLKSEN C., SEEBER G.: *Analyse von SCAR GPS Epochen- und Permanentstationsdaten aus der Antarktis mit GIPSY/OASIS-II*; In: Dtsch. Geod. Komm., Reihe B, München, 2000, Nr. 310, p. 91-108
- MEYER F., SEITZ F., MÜLLER J.: *An Algorithm for Reliable Normal Point Calculation of Noisy LLR Measurements*; In: Laser Radar: Ranging and Atmospheric Lidar Techniques III, SPIE-Proceedings, Vol. 4546, No. 29, p. 154-159, U. Schreiber, C. Werner, G. Kamerman, U. Singh (eds.), 2002.
- MICHEL I.: *Mit ESRI-GIS ins System ETRS89*; In: Vermess. Brandenburg, Potsdam 4 (1999) 2, p. 52-53
- MÜLLER A.: *SAPOS in Rheinland-Pfalz: Grundlagen und Aufbau*; In: Nachr.-Bl. Vermess.-Katasterverwalt. Rheinl.-Pfalz, Koblenz 42 (2000) 4, p. 254-260 MÜLLER J.: *Zeitskalen*; In: 3. DFG-Rundgespräch zum Thema Bezugssysteme, Wetzell, April 28-29, 1998, Mitteilungen des BKG, Band 5, p. 77-83, ed. by M. Schneider, 1999.
- MÜLLER J., NORDTVEDT K., SCHNEIDER M., VOKROUHLICKY D.: *Improved Determination of Relativistic Quantities from LLR*; In: Proceedings of the 11th International Workshop on Laser Ranging Instrumentation, held in Deggendorf, Germany, Sept. 21-25, 1998, Mitteilungen des BKG, Band 10, p. 216-222, 1999.
- MÜLLER J., NORDTVEDT K., SCHNEIDER M., VOKROUHLICKY D.: *What can LLR provide to Relativity?*; In: Proceedings of the 8th Marcel Grossmann Meeting on General Relativity, Jerusalem, Israel, June 22-27, 1997, ed. by T. Piran, p. 114-121, World Scientific, 1999.
- MÜLLER J., EGGER D., REICHHOFF B., SCHNEIDER M., SCHREIBER U.: *Lunar Laser Ranging at its Best*; In: Towards an Integrated Global Geodetic Observing System (IGGOS), Proceedings of the IAG Section II Symposium, held in Munich, Germany, Oct. 5-9, 1998, IAG Symposia, Vol. 120, p. 161-164, Springer Verlag, 2000.
- MÜLLER J.: *FESG/TUM, Report about the LLR Activities*; ILRS Annual Report 1999, M. Pearlman and L. Taggart (eds.), p. 204-208, 2000.
- MÜLLER J.: *FESG/TUM, Report about the LLR Activities*; ILRS Annual Report 2000, M. Pearlman, M. Torrence, L. Taggart (eds.), p. 7-35 – 7-36, 2001.
- MÜLLER J.: *FESG/IFE, Report about the LLR Activities*; ILRS Annual Report 2001, M. Pearlman M. Torrence and L. Taggart (eds.), 2002.
- National Reports*: In: Mitt. d. Bundesamtes f. Kartographie und Geodäsie, Frankfurt am Main, 2002, Bd. 23, p. 198-276
- PROFT J., SORGE B.: *Umstellung auf das Lagebezugssystem ETRS89 im Land und im Landkreis Märkisch-Oderland*; In: Vermess. Brandenburg, Potsdam 4 (1999) 2, p. 22-29
- PUJOLE R., CIFUENTES F. H., DE NEIRA J. L. C. S., BARRADO J.: *The Balear98 Project : Final results*; Report on the Symposium of the IAG sub-commission for Europe (EUREF) in Tromso, 22-24 June 2000, Verlag der Bayerischen Akademie der Wissenschaften, München 2000
- REIGBER C., JAKOWSKI N., GALAS R., WICKERT J., KÖNIG, R., WEHRENPENNIG A.: *GFZ and DLR contribution to a GPS ground network to support the CHAMP mission*; In: International Association of Geodesy Symposia, 120, Springer, Berlin Heidelberg 2000, p. 222-224
- RENNEN M., NIEMEIER W., SALBACH H., DIETRICH R., DACH R., IHDE J., ENGELHARDT G., LINDNER K., MAYER M., MENGE F., PERLT J., POHL M., SCHENKE H. W., SCHÖNE T., SEEBER G., VÖLKSEN C.: *Effects of software-noise and reference-frame noise on GPS-results, shown for an extended GPS network in Antarctica*; IUGG 99 Meeting, 19 July to 30 July, Birmingham/UK, abstracts, A. 416, 1999.
- RIEPL S., SCHLÜTER W., SCHREIBER U.: *Evaluation of an SLR Adaptive Optics System*; Remote Sensing; 20-24 Sept. 1999, Florence/Italy, Proceedings of SPIE
- RIEPL S., SCHREIBER U., SCHLÜTER W.: *Improvements of SLR by Adaptive Optics*; 11th International Workshop on Laser Ranging, Mitteilungen des BKG, Band 10 und Band 11, Frankfurt 1999
- RIEPL S.: *Experimental Verification of the MARINI-MURRAY Model by Two Colour SLR*; Matera, Laser Ranging Workshop 2000
- RIEPL S., SCHLÜTER W.: *Normal Point Algorithm for Reduction of two Colour SLR Observations*; 2001 Kluwer Academic Publishers, Netherlands, Surveys in Geophysics 00: 1-8, 2001
- ROSSBACH U.: *Reference systems used in global navigation satellite systems*; In: International Association of Geodesy Symposia, Vol. 120, Springer, Berlin Heidelberg 2000, S. 110-113
- ROTHACHER M.: *Die Aktivitäten des Rechenzentrums CODE im Rahmen des IGS*; In: Schriftenreihe Dtsch. Verein f. Vermess.-wesen, Stuttgart, 1999, Bd. 35, p. 144-160
- ROTHACHER M.: *Hochgenaue regionale und kleinräumige GPS-Netze: Fehlerquellen und Auswertestrategien*; In: Mitt.-Bl. Dtsch. Verein f. Vermess.-wesen, Landesverein Bayern, München 52 (2000) 2, p. 153 172
- ROTHACHER M.: *Towards an integrates global geodetic observing system*; In: International Association of Geodesy Symposia, 120, Berlin, 2000, p. 41-52
- RUMMEL R., DREWES H., BOSCH W., HORNIK H.: *Towards an Integrated Global Geodetic Observing System (IGGOS)*; In: International Association of Geodesy Symposia; Vol. 120, Springer, Berlin Heidelberg 2000, 261 p.
- RUMMEL R., HECK B.: *Some critical remarks on the definition and realization of the EVRS*; Torres J.A., Hornik H. (Hrsg.): Reports on the Symposium of the IAG Subcommission for Europe, Commission X, held in Tromso, 22 – 24 June 2000. Veröffentlichung der Bayerischen Kommission für die Internationale Erdmessung, Astro-geodätische Arbeiten, Heft Nr. 61, 2001, p. 114 – 115
- RUMMEL R.: *Global integrated geodetic and geodynamic observing system (GIGGOS)*; In: International Association of Geodesy Symposia; Vol. 120, Berlin, Springer 2000, P. 253-260
- SACHER M, IHDE J., CELMS A., ELLMANN A.: *The first UELN stage is achieved: further Stepps are planned*; In: Veröff. Bayer. Komm. Int. Erdmess., Bayer. Akad. d. Wiss., Astron.-geod. Arb., München, 1999, H. 60, p. 87-94
- SACHER M., IHDE J., SEEGER H.: *Preliminary transformation relations between national European height systems and the United European Levelling Network (UELN)*; In: Veröff. Bayer. Komm. Int. Erdmess., Bayer. Akad. d. Wiss., Astron.-geod. Arb., München, 1999, H. 60, p. 80-86
- SACHER M., LANG H., IHDE J.: *Status and results of the adjustment and enlargement of the United European Levelling Network 1995 (UELN-95)*; In: Report on the Symposium of the IAG Subcommission for Europe (EUREF), Frankfurt am Main, 1999, p. 131-141

- SACHER M., IHDE J., SCHOCH H., GIRRULAT D., MOLENDIJK R., SCHMIDT K.: *Preliminary results of test computations as a first step to a kinematic height network*; In: Veröff. Bayer. Komm. Int. Erdmess., Bayer. Akad. d. Wiss., Astron.-geod. Arb., München, 2000, H. 61, p. 116-125
- SACHER M., IHDE J., CORCODEL S.: *Status of the UELN/EVS database and results of the last UELN adjustment*; In: Veröff. Bayer. Komm. Int. Erdmess., Bayer. Akad. d. Wiss., Astron.-geod. Arb., München, 2000, H. 61, p. 126-131
- SACHER M., IHDE J., PARSELIUNAS E.: *Status of the UELN/EVS data base: activities between June 2000 and May 2001 and future plans*; In: Mitt. d. Bundesamtes f. Kartographie und Geodäsie, Frankfurt am Main, 2002, Bd. 23, p. 146-153
- SCHAER S., BROCKMANN E., BEUTLER G., WIGET A., ROTHACHER M., WILD U.: *The impact of the atmosphere and other systematic errors on permanent GPS networks*; In: International Association of Geodesy Symposia, Vol. 121, Springer, Berlin Heidelberg 2000, p. 373-380
- SCHLÜTER W., HASE H., BÖER A., DASSING R., KILGER R.: *Transportable Integrated Geodetic Observatory*; Paper prepared for the IGGOS-Symposium München, Oktober 1998 (im Druck)
- SCHLÜTER W., IHDE J., WEBER G., PAHLER K.-H.: *National report of Germany*; In: Veröff. Bayer. Komm. Int. Erdmess., Bayer. Akad. d. Wiss., Astron.-geod. Arbeiten, München, 1999, H. 60, p. 169-172
- SCHLÜTER W., DASSING R., KILGER R., SCHREIBER U.: *The Fundamental Station Wettzell - current status and future plans*; Proceedings of the International Workshop on Geodetic Measurements by the collocation of Space Techniques on Earth (GEMSTONE) January 25-28, 1999, Koganei, Tokyo/Japan
- SCHLÜTER W., HASE H., RÖTTCHER K., STÖGER R., LANG H., ZERNECKE R.: *Actual Results of the Local Survey at the FS-Wettzell*; Proceedings of GEMSTONE, Koganei, Tokio, January 25-28, 1999
- SCHLÜTER W., GURTNER W., HARSSON B. G., IHDE J., WÖPPELMANN G.: *Report of the EUVN Working Group*; In: Report on the Symposium of the IAG Subcommission for Europe (EUREF), Frankfurt am Main, 1999, p. 7-10
- SCHLÜTER W., HASE H., BÖER A.: *TIGO – a geodetic observatory for the improvement of the global reference frame*; Prepared for the EOS/SPIE Symposium on Remote Sensing, Sept. 20-24, 1999, Florence/Italy, Proceedings of SPIE
- SCHLÜTER W., HASE H., BÖER A., RIEPL S., ALVAREZ J., CECIONI A.: *Progress of the TIGO-Project*; CSTG-Bulletin 16, München 2000
- SCHLÜTER W., HAYO H., BÖER A., RIEPL S., ALVAREZ J., CECIONI A.: *Progress of the TIGO-Project*; Proceedings of the 4th Workshop, Shanghai, P.R. China, 14-19 May, 2001, (APSG 2001)
- SCHLÜTER W., HIMWICH E., NOTHNAGEL A., VANDENBERG N., WHITNEY A.: *IVS and its important role in the maintenance of the global Reference System*; 33rd COSPAR Scientific Assembly Warsaw/PL, 16.-23. July 2001
- SCHLÜTER, W.: *Die Aktivitäten der Fundamentalstation Wettzell*; DGK-Heft (DFG-Rundgespräch 2001/Höllenstein)
- SCHLÜTER W., HASE H., BÖER A., RIEPL S., CECIONI A.: *TIGO starts its operation in Concepción in 2002*; CSTG, Bulletin 17, München, Sept. 2002
- SCHLÜTER W., HIMWICH E., NOTHNAGEL A., VANDENBERG N., WHITNEY A.: *IVS and its important Role in the Maintenance of the Global Reference Systems*; Adv. Space Res. Vol. 30, No. 2, pp.145-150, 2002, COSPAR
- SCHLÜTER W., SCHUH H., VANDENBERG N.: *Evolving IVS Products and Related Observing Programs*; EGS-Proceedings special issue of Physics and Chemistry of the Earth, Elsevier-Verlag (April 2002), in preparation
- SCHLÜTER W., SEEGER H., BÖER A., DASSING R., HASE H., KLÜGEL T., KILGER R., REINHOLD A., RIEPL S., ROTHACHER M., SCHLICHT A., SCHREIBER U., WOJZDZIAK R.: *Die geodätischen Fundamentalstationen Wettzell und TIGO und die Antarktisstation O'Higgins*; Reihe BKG, 50 Jahre BKG (Juli 2002)
- SCHLÜTER W., VANDENBERG N.: *Prospective Development of the International VLBI Service for Geodesy and Astrometry over the next few years*; vorgesehen für CSTG-Bulletin Nr. 17, July 2002
- SCHLÜTER W., ZERNECKE R., KLÜGEL T.: *Local Survey at the FS-Wettzell*; EGS-Nice/F, EGS02-A-03965, 03.05.2002
- SCHLÜTER W., VANDENBERG N.: *Geodetic VLBI – wishes and limitations, New Technologies in VLBI Korea*; ASP Conference Series, Gyeong-ju Korea 2003
- SCHÖN S., KUTTERER H., MAYER M., HECK B.: *On the Datum Quality of a Continental ITRF96-based Reference Network in Antarctica*; Interner Bericht, Geodätisches Institut der Universität Karlsruhe, 2000
- SCHÖN S., KUTTERER H., MAYER M., HECK B.: *A study on the transfer of the ITRF datum to a GPS network in Antarctica*; Sideris M. (Hrsg.): Gravity, Geoid and Geodynamics 2000; IAG Int. Symposium, Banff/Canada, July 31 – Aug. 4, 2000. IAG Symposia, Vol. 123 (2001), Springer Verlag, p. 29–34
- SCHÖN S.: *On the datum quality of a continental ITRF96-based reference network in Antarctica. Publications du Laboratoire de Recherche en Géodésie (LAREG)*; Série Mémoire de Stage MS15. Ecole Nationale des Sciences Géographiques, Marne-la-Vallée, France, 2001
- SCHREIBER U., HAUFE K.H., PROCHAZKA I.: *Concept of a Pet4/LabView-Control System*; Proceedings of the 11th Workshop on Laser Ranging, 413-420, 1999
- SCHREIBER U., HAUFE K.H.: *Timewalk in Avalanche Photo Diodes*; Proceedings of the 11th Workshop on Laser Ranging, 413-420, 1999
- SCHREIBER U., KAWANO N., YOSHINO T., DEGNAN J., NORDTVEDT K., MÜLLER J., SCHLÜTER W., KUNIMORI H.: *Laser Ranging and VLBI for the Selene-II Mission*; Proceedings of the International Workshop on Geodetic Measurements by the collocation of Space Techniques on Earth (GEMSTONE) January 25-28, 1999, Koganei, Tokyo/Japan
- SCHREIBER U., SCHLICHT A., HAUFE K.H.: *Systematic Biases in Laser Ranging Measurements*; In: "Proceedings of the SPIE", Vol. 3865, p. 64-73 (1999)
- SCHREIBER U., SCHLICHT A., HAUFE K.H.: *Systematic Biases in Laser Ranging Measurements, Symposium on Satellite Remote Sensing*; 20.-24. Sept. 99, Florence, Italy, Proceedings of the SPIE, Vol. 3865, p. 64-73
- SEEGER H., ALTINER Y.: *Stand und Perspektiven von EUREF*. In: Gerd Riedl und Hermann Seeger (eds): GPS-Praxis und Trends, DVW Schriftenreihe 35/1999, Wittwer Verlag, p. 238-250
- SPATA M., AHRENS B., GÜNTHER G., IRSEN W., RUF B.: *Die Verknüpfung ellipsoidischer Höhen und Landeshöhen durch Undulationen: neues NN-Undulationsmodell 2000*; In: Nachr. Öffentl. Vermess.-dienst Nordrhein-Westfalen, Bonn 23 (2001) 1, p. 59-67
- VÖLKSEN C.: *Aktuelle GPS-Anwendungen in Island*; In: Wiss. Arb. Fachricht. Vermess.-wesen. Univ. Hannover, 2001, Nr. 239, p. 113-122

- WANNINGER L.: *The performance of virtual reference stations in regional GPS networks under severe ionospheric conditions*; In: Rep. geod., Warszawa, 1999, Nr. 5 (46), p. 63-70
- WANNINGER L.: *Virtuelle Referenzstation in regionalen GPS-Netzen*; In: Schriftenreihe Dtsch. Verein f. Vermess.-wesen, Stuttgart 1999, Bd. 35, p. 199-212
- WILLIS P., NOLL C., SLATER J., WEBER R., BEUTLER G., NEILAN R. E., GURTNER W., HEIN G.: *The IGEX-98 campaign: Highlights and perspective*; In: International Association of Geodesy Symposia, Vol. 121, Springer, Berlin Heidelberg 2000, p. 22-25
- WÖPPELMANN G., ADAM J., GURTNER W., HARSSON B. G., IHDE J., SACHER M., SCHLÜTER W.: *Status report on sea-level data collection and analysis within the EUVN project*; In: Veröff. Bayer. Komm. Int. Erdmess., Bayer. Akad. d. Wiss., Astron.-geod. Arb., München, 2000, H. 61, p. 146-153
- WZIONTEK H., LELGEMANN D.: *Zur Bedeutung relativer Höhenanomalien für die Koordinatentransformation von DHDN in das ETRS89*; In: Zeitschrift Vermess.-wesen, Stuttgart 124 (1999) 5, p. 166-169
- ZEBHAUSER B.: *Realisierungen von Bezugssystemen*; In: Mitt. d. Bundesamtes f. Kartographie und Geodäsie, Frankfurt am Main, 1999, Bd. 5, p. 70-76

Permanent GPS networks and real-time positioning

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Global and regional permanent networks

At the GeoForschungsZentrum (GFZ) Potsdam group on "Active global and regional networks, including SAPOS", the number of permanent GPS receivers operated by GFZ Potsdam has steadily increased during the last years and amounts to 54 totally in early 2003. For supporting the classical IGS activities 15 globally distributed stations are operated with 30 sec sampling rate and hourly data retrieval except one station providing daily data only (RAMATSCHI et al., 2000).

During the last four years the activities were significantly enlarged for operational requirements of the satellite missions CHAMP and GRACE. A global high-rate (1 sec), low latency (15 minutes) sensor station network was established in 1999 for the CHAMP/GRACE orbit recovery and for monitoring the neutral atmosphere and the ionosphere (GALAS et al., 2001; GALAS, KÖHLER, 2001; REIGBER et al., 1998). Presently this network comprises 15 stations and the data are available via the CHAMP ISDC at GFZ and in the global IGS data centers. This network has been integrated into the global IGS high-rate network for supporting the IGS LEO activities.

The various GFZ projects for studying regional crustal motions are supported by additional 9 permanent sites in South America and Canada. A dedicated 3-station array for monitoring volcanic activities was established in Mexico (GALAS et al., 1998). For the calibration of altimeter missions (ENVISAT, TOPEX, ERS, JASON) a moored buoy in the North Sea was equipped with a GPS receiver and is operating since 2001.

Following the IGS workshop "Towards Realtime" in April 2002, the Subcommittee EUREF of IAG's commission X decided to contribute to the real-time dissemination of GNSS data over the Internet. An HTTP-streaming technique called "Networked Transport of RTCM via Internet Protocol" (Ntrip) has been developed (WEBER, 2002, GEBHARD and WEBER, 2003). Its implementation within the framework of EUREF is under way.

In the EUREF group with its European Permanent Network (EPN) the Bundesamt für Kartographie und Geodäsie (BKG) contributed to the computation of the ITRF2000 (BECKER et al., 2000). BKG and the Bayerische Akademie der Wissenschaften (BEK) are two is one of the 16 local EPN analysis data centers. The sub-networks analyzed by each of the

centers are combined by BKG into the official weekly EPN solution. The processing methodology and strategy were improved with guidelines for a standardized processing and investigations of problem sites (BRUYNINX et al., 2000). Recent changes in the analysis of the 16 EPN subnetworks (performed by the Local Analysis Centers) and their combination (performed by BKG) are given in HABRICH, 2002.

National permanent networks

The permanent network of the survey authorities in Germany named SAPOS (ADV, 2002) was almost completed in the period 1999 to 2003, the number of sites being 261 in spring 2003. This network provides DGPS and RTK services for positioning and navigation purposes (WEBER et al. 1999). The networks are processed in real time by central processing facilities in each federal state and data is disseminated by GSM phone and internet (DICK, 2001, WEBER, 2001, ROSENTHAL, 2001a,b). Both the concept of "Virtual Reference Stations" and aerial correction surface-parameters are realized in parallel (LANDAU, 2001, HUCK et al. 2002, WÜBBENA, 2002).

The German GPS Reference Network (GREF) operated by the BKG is gradually improved to a real time GPS/GLONASS network since 2000. The real time network stations are combined with gravity measurements and will be connected to the European leveling network. GREF realizes the connection between the EPN and SAPOS.

The multi-purpose concept of SAPOS and other services in the framework of European DGPS services was discussed by (AUGATH, 2000, 2001a, 2001b).

In a cooperation with Brazil and sponsored by the German Government the Hanover University fostered the development of a RTK reference station network in Brazil. Special topics of this project were the development of a state-space model for the network (WÜBBENA, WILLGALIS, 2001) and the investigation of ionospheric disturbances in view of the equatorial and sun-cycle conditions (WILLGALIS, et al., 2001). A further aspect was the use of active networks for cadastral applications in Brazil (WILLGALIS et al., 2002).

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Networks for ground based GPS Meteorology

The use of GPS for detailed short-range numerical weather prediction requires observational information with high spatial and temporal resolution. The GFZ, leading the Helmholtz Association's Strategy Fund Project GASP (GPS Atmospheric Sounding Project), established a near real-time network of 21 stations at synoptic sites of the German Weather Service (DWD), (DICK et al., 2001). The network for this project was steadily densified by using stations from the SAPOS network containing now 140 stations (REIGBER et al., 2002).

The GFZ is processing the hourly data in near real time NRT (GFZ, 2003). The analysis is finished within 10 to 20 minutes with an availability of the GPS-data close to 90%. The final product is the Integrated Water Vapor (IWV) with a precision of about 1 to 2 mm. In cooperation with the DWD the IWV has been monitored and assimilation experiments have been carried out to test the impact of the new observations in the operational non-hydrostatic limited-area-model. The GFZ and DWD research is participating in the European research cooperation COST-Action 716 "Exploitation of Ground-Based GPS for Climate and Numerical Weather Prediction Applications" (ELGERED, 2003).

EUREF's Permanent Network (EPN) has been used extensively for the estimation of troposphere parameters in post-processing modus. Weekly combinations of actually 16 national European solutions are carried out since 2001 (KANIUTH, 2000, SÖHNE and WEBER, 2002)

Models and Strategies for RTK Positioning

Various studies focused on permanent network sites characteristics, the GPS data quality monitoring (AUGATH et al., 2003; LANDAU, 2000), models for RTK networks in view of ambiguity resolution and parameter representation as well as network design and data dissemination.

Site characteristics can be determined by analyses of the carrier phase data for multipath and diffraction (WANNINGER, MAY, 2000, 2001; WANNINGER et al., 2000; AUGATH, 2003), corrections at the level of undifferenced phase observations seem feasible.

The concept of modeling Virtual Reference Stations was studied in detail by (WANNINGER, 1999a, 2000a). It was extended to large scale kinematic positioning by the use of semi-kinematic virtual reference sites (WANNINGER, 2002; VOLLATH et al., 2001). Severe ionospheric disturbances play a major role in RTK positioning and their mitigation and counter-measures were derived in (WANNINGER, 1999b,c, 2000b,c).

The general methodology for RTK modeling was investigated by (LANDAU et al., 2001, WÜBBENA et al., 2001, WÜBBENA, WILLGALIS, 2001). (LEINEN, 2002) introduces an alternative approach based on fuzzy-logic as replacement for the conventional stochastic approach. (KEENEN et al., 2002) discuss the future formats for RTK data dissemination.

References

- Adv; <http://www.sapos.de>, 2002
- AUGATH W.; *Europäische Entwicklungen und ihr Bezug zu Radionavigations-plänen*; DVW-Schriftenreihe Nr. 41, p. 36-46, Wittwer-Verlag; Stuttgart, 2000
- AUGATH W.; *Europäische DGPS-Dienste*; Tagungsband des DGON-Symposiums POSNAV 2001, p. 67-76; Bonn, 2001a
- AUGATH W.; *Beiträge des Vermessungs-wesens zur Ortung und Navigation im Wandel*; Tagungsband der DGON-Jubiläumsveranstaltung (1951 - 2001), p. 195-210; Bonn, 2001b
- AUGATH W., BLUMENBACH TH., WILDT ST.; *Qualitätssicherung bei Referenz-stationen und in Referenzstationsnetzen*; SAPOS 2002 Symposium; Hannover, 21.-23.05. 2002
- AUGATH W.; *Signal and Station Validation of GNSS Permanent Stations for Precise Positioning, Weather Forecast and Navigation*; 5th Setmana Geomatica, Cartography, Tele-matics and Navigation; Barcelona. 11.-14.02.2003
- BECKER M., FRANKE P., WEBER G., INEICHEN D., MERVART L.; *Report on the Symposium of the IAG Subcommission for Europe (EUREF)*; held in Tromso, 22.-24. June 2000; EUREF Contribution to the ITRF2000 and Analysis Coordinator Report for 8/99 to 6/00; Torres and Hornik (Edts.); Veröffentlichungen der Bayerischen Kommission für die Internationale Erdmessung der Bayerischen Akademie der Wissenschaften, Astronomisch-Geodätische Arbeiten, No. 61, München, pp. 31-36, 2000. ISSN: 0340-7691, ISBM: 3 7696 9623 9, 2000
- BRUYNINX C., BECKER M., STANGL G.; *Regional Densification of the IGS in Europe Using the EUREF Permanent GPS Network (EPN)*; IGS Network Workshop 2000, Soria Moria, Oslo 12-14 July 2000
- DICK G., GENDT G., REIGBER CH.; *First Experience with Near Real-Time Water Vapor Estimation in a German GPS Network*; Journal of Atmospheric and Solar-Terrestrial Physics 63, 1295-1304, 2001
- DICK H.-G.; *Erste Erfahrungen mit der Vernetzung von SAPOS-Referenzstationen in Baden-Württemberg*; In: GPS-Trends und Realtime-Anwendungen; Beitr. 52, Bd. 41, p. 128-152 Stuttgart, 2001
- ELGERED G.; <http://www.oso.chalmers.se/geo/cost716.html/>, March 2003
- GALAS R, REIGBER CH., MICHEL G.; *Current Status and Perspectives of the GFZ GPS-Based Volcano Monitoring system*; EOS Supplement; WPGM, 1998
- GALAS R, WICKERT J., BURGHARDT W.; *High Rate Low Latency GPS Ground Tracking Network for CHAMP*; Phys. Chem. Earth (A), Vol. 26, No.6-8, pp. 649-652, 2001
- GALAS R, KOEHLER W.; *A Binary Exchange Format for GPS Data*; Phys. Chem. Earth (A), Vol. 26, No. 6-8, pp. 645-64, 2001
- GEBHARD H. and WEBER G.; *Networked Transport of RTCM via Internet Protocol*. http://igs.ifag.de/index_ntrip.htm, March 2003
- GFZ; http://www.gfz-potsdam.de/pb1/pg1/gasp1/main_GASP1.html; 2003

- HUCK B., ROSS A., RÜFFER J.; *GNSS-Referenznetzkonzepte: Ihre Realisierungen im praktischen Vergleich*; In: Vermessungsingenieur, Wiesbaden 52 4, p. 266-269, 2002
- KANIUTH K.; *The EUREF Permanent Network: ocean tide loading, height and troposphere estimates*; In: Veröff. Bayer. Komm. Int. Erdmess., Bayer. Akad. d. Wiss., Astron.-geod. Arb., H. 61, p. 69-74; München, 2000
- KEENAN, C.R., B.E. ZEBHAUSER, H.J. EULER, G. WÜBBENA.; *Using the Information from Reference Station Networks: A Novel Approach Conforming to RTCM V2.3 and Future V3.0. IEEE PLANS 2002*; April 15 to 18, 2002, Palm Springs, CA, 2002
- LANDAU H.; *Zur Qualitätssicherung in GPS-Referenzstationsnetzen*; In: Ing.vermess. 2000: 13. Int. Course Engin. Survey, Beiträge/Contributions, München, 13.-17. März 2000, Bd. 33, p. 277-290, Stuttgart, 2000
- LANDAU H.; *GPS-Vermessung mit Hilfe von virtuellen Referenzstationen: Theorie, Analyse und Applikationen*; In: GPS-Trends und Realtime-Anwendungen: Beitr. 52, Bd. 41, p. 153-169, Stuttgart, 2001
- LANDAU H., VOLLATH U., DEKING A., PAGELS CHR.; *Virtual Reference Stations –Recent Innovations by Trimble*; Proceedings of the International Satellite Symposium, Tokyo, Japan, November 15-16; 2001
- LEINEN S.; *Fuzzy-Logic based GPS On-The-Fly Ambiguity Search*; Proceedings of First International Symposium on Robust Statistics and Fuzzy Techniques in Geodesy and GIS; Zürich, Switzerland, March 12-16, 2001, 2002
- RAMATSCHI M, NEUMEYER J., NISCHAN TH.; *Status report of IGS stations monitored by GFZ*; Technical Report IGS, 2000
- REIGBER CH., GALAS R., KOENIG R., JAKOWSKI N., WICKERT J., WEHRENFENNIG A.; *GFZ and DLR Contribution to a GPS Ground Network to Support the CHAMP Mission*; Proc. IAG Section II Symposium, Munich, pp 222-224, October 5-9, 1998
- REIGBER CH., GENDT G., DICK G., TOMASSINI M.; *Near-real-time water vapor monitoring for weather forecasts*; GPS-World, Vol. 13, No. 1, pp. 18-27, 2002
- ROSENTHAL, G.; *Requirements for the implementation of geodetic reference systems and their compliance with GNSS reference stations networks*; In: International Symposium and Exhibition. Geodetic, Photogrammetric and Satellite Technologies - Development and Integrated applications; 08-09 November 2001, Sofia, Bulgaria, publisher: FIG, ISPRS, ICA, Union of Surveyor and Land Managers in Bulgaria, EGOS, Geodetic Institute University of Hanover - Germany, p. 82-91, Sofia, 2001a
- ROSENTHAL, G.; *SAPOS® The German National Satellite Positioning Service, presented at the 1st Common Baltic Symposium, GPS-Heighting based on the Concept of a Digital Height Reference Surface (DFHRS) and related Topics- GPS-Heighting and National-wide Permanent GPS Reference Systems, Riga, Latvia, June 11, 2001b*
- SÖHNE, W., G. WEBER: *EUREF Troposphere Combination at BKG - First Results and Improvements*; Proceedings of the COST Action 716 Workshop "Exploitation of Ground-Based GPS for Meteorology", GeoForschungsZentrum Potsdam; January 28-29, 2002
- VOLLATH U., DEKING A., LANDAU H., PAGELS CHR.; *Long Range RTK Positioning using Virtual Reference Stations*; Proceedings of the International Symposium on Kinematic Systems in Geodesy; Geomatics and Navigation, Banff, Canada; June 2001
- VOLLATH U., LANDAU H., CHEN X., DOUCET K., PAGELS CHR.; *Network RTK versus Single Base RTK – Understanding the Error Characteristics*; Proceedings of the 15th International Technical Meeting of the Satellite Division of the Institute of Navigation; Portland, Oregon, USA; September 2002
- WANNINGER L.; *Virtuelle Referenz-stationen in regionalen GPS-Netzen*; DVW-Schriftenreihe 35/99, p. 199-212; 1999a
- WANNINGER L.; *Der Einfluss ionosphärischer Störungen auf die präzise GPS-Positionierung mit Hilfe virtueller Referenzstationen*; Zeitschrift für Vermessungswesen 124:322-330; 1999b
- WANNINGER L.; *The Performance of Virtual Reference Stations in Active Geodetic GPS-networks under Solar Maximum Conditions*; Proceedings of ION GPS '99, Nashville, 1999, 1419-1427; 1999c
- WANNINGER L., MAY M.; *Carrier Phase Multipath Calibration of GPS Reference Stations*; Proc. of ION GPS 2000; Salt Lake City, UTM, 2000
- WANNINGER L., FREVERT V., WILDT S.; *Der Einfluss der Signalbeugung auf die präzise Positionierung mit GPS*; Zeitschrift für Vermessungswesen, 125, p. 8-16, 2000
- WANNINGER L.; *Der Einfluss der Ionosphäre auf die Positionierung in Referenzstationsnetzen*; 3. SAPOS-Symposium, München, 23./24.05.2000, p. 129-140, 2000b
- WANNINGER L.; *The Performance of Virtual Reference Stations in Active Geodetic GPS-Networks under Solar Maximum Conditions*; Proc. of ION GPS 99, Nashville TN, p. 1419-1427, 2000c
- WANNINGER L.; *Präzise Positionierung in regionalen GPS-Referenzstationsnetzen*; Deutsche Geodätische Kommission, Reihe C, Heft Nr. 508, 68 p., München, 2000a
- WANNINGER L. MAY M.; *Carrier Phase Multipath Calibration of GPS Reference Stations*, Navigation, 48:113-124, 2001
- WANNINGER, L.; *Virtual Reference Stations for Centimeter-Level Kinematic Positioning*, Proc. of ION GPS 2002, Portland, Oregon, 1400-1407, 2002
- WEBER G., BECKER M., FRANKE P.; *GPS-Permanentnetze in Deutschland und Europa*; In: Schriftenreihe Dtsch. Verein f. Vermess.-wesen, Bd. 35, p. 251-265; Stuttgart 1999
- WEBER, G.; *The SAPOS® System in Germany*; 3rd Asia Pacific Rim Meeting, International Information Subcommittee (IISC), Civil GPS Service Interface Committee (CGSIC); Tokyo, Japan, 6-9 Feb 2001
- WEBER, G.; *Echtzeit-Übertragung von RTCM-Daten über Internet und Mobilfunk*; Beitrag zum 57. DVW-Seminar „GPS 2002: Antennen, Höhenbestimmung und RTK Anwendungen“, 16.-17. Sep 2002, Karlsruhe, Schriftenreihe Deutscher Verein für Vermessungswesen, Band 44, p. 107-116, Stuttgart, 2002
- WILLGALIS S., SEEBER G., MENGE F., KRUEGER C.P., ROMAO V.M.C.; *Implementation of a GPS Reference Network for Precise Real Time Positioning in Recife, Brazil*; p. 1071-1078; ION GPS 2001

- WILLGALIS S., SEEGER G., KRUEGER C.P., ROMÃO V.M.C.; *A Real Time GPS Reference Network for Recife, Brazil, Enabling Precise and Reliable Cadastral Surveys*; FIG XXII International Congress, Com. 5.; Washington, D.C. USA; April 19-26 2002.; 2002
- WÜBBENA G., WILLGALIS S.; *State Space Approach for Precise Real Time Positioning in GPS Reference Networks*; Internat. Symp. on Kinematic Systems in Geodesy, Geomatics and Navigation (KIS2001); Banff, Kanada, p. 72-79, 2001
- WÜBBENA, G., A. BAGGE, M. SCHMITZ (2001). *Network-Based Techniques for RTK Applications*. Presented at the GPS Symposium, GPS JIN 2001, GPS Society, Japan Institute of Navigation, November 14.-16., 2001, Tokyo, Japan, 2001
- WÜBBENA, G.; *Zur großräumigen Vernetzung von GNSS-Referenzstationen*. Arbeitsgemeinschaft der Vermessungsverwaltungen der Länder der Bundesrepublik Deutschland AdV, 4. SAPOS Symposium - SAPOS verbindet ..., 21.-23. Mai 2002, Hannover, 139-148, 2002.

Positioning for close range and engineering applications

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Close range applications of GPS

In the last four years the application of high precision differential GPS came to wide practical use in engineering surveying. Measuring principles are static and kinematic DGPS, using phase observations. As reference station partially the established permanent GPS-networks like SAPOS, ASCOS are used, but mainly here project related reference stations were set-up. HOLLMANN (2000) gives a comprehensive and competent overview on various problems related to GPS observations when establishing local geodetic networks. ILLNER (2002) illustrates, that even with RTK-GPS a precision of several mm can be reached, if repeated observations and local reference stations or near-by SAPOS stations can be used.

Main applications of GPS in close range were the setting-out of large scale structures, like tunnels (SCHÄFER & WEITHE 2002), bridges (KRAUSE 2000), power stations, airports and railway constructions and track control.

A further complex is the use of continuous GPS for the monitoring of longterm deformation processes of structures. Here several systems are developed, e.g. KÄLBER et.al. (2001), BÄUMKER et.al. (2000). All these systems make use of phase observations in GPS and work with local reference stations to avoid problems with atmospheric disturbances. Some use L1 low-cost receivers, others L1 and L2 observations. Further on the "raw" GPS results are in general smoothed by applying simple or sophisticated filtering (BACKHAUSEN et.al. 1999). The stated accuracy of these systems is in the range of a few mm. Reports on experimental use of these monitoring systems (KORITTKKE & PALTE 2002) prove the high reliability of these concepts and mainly the stated accuracies.

Positioning with terrestrial techniques

Laserscanning techniques

A highlight in the past four years was the advent of laserscanning in geodesy. By this innovative technique the geometry of structures will be determined or "captured" by a dense, regular distributed raster of points and not – as is usual in geodesy – by a limited number of representative points. The primary observations in laserscanning are ranges, which are physically based on three principles: time of flight, phase differences or optical triangulation. The measuring beam itself is varying stepwise in horizontal and vertical direction, where the size of the steps can be preset or are fixed. An overview on available laserscanners and their characteristics is given by NIEMEIER, THOMSEN and SCHÄFER (2002b),

details on specific instruments are given in RUNNE et.al. (2001). A description of specific instruments and their potential can be found by HEINZ et.al. (2002), MÜCKE (2002), SCHOCK (2002) STEPHAN et.al. (2002) and WEHR (2000). A typical application in a steel factory plant is given by STAIGER & MÜHL (2002).

The main task in laserscanning is the modelling of the geometry of structures or building out of the 3D point clouds (BRINGMANN 2002), which are the basic output of a scan. This task can be derived into two main steps

a) Estimation of the geometric primitives, like edges, corners, planes and higher order surfaces, which describe the geometry adequately. For edge detection HOVENBITZER (2001) has derived a strategy, using the distance increments between neighboring points. A rapid change in these increments is an indicator for a sharp change in the geometry, e.g. an edge. A more general concept is developed by KERN (2003) and KERN et.al. (2002), where the definition of basic surfaces starts with a triangulation of the laserscanning data, the inclusion of roughness parameters and is then based on the application of adequate statistical testing.

b) The combination of different scans is necessary to determine a complete geometry of 3D-structures, as a scan can only give information of one side of an object. For this connection of scans the use of identical surfaces (NIEMEIER & KERN 2001), spherical elements of different diameter (SCHOCK 2002) and special active targets (NIEBUHR 2002) are recommended.

An interesting aspect is the combination of 3D point clouds, as determined by laserscanning, with digital images (SCHWEMANN & EFFKEMANN 2002), (KERN 2003). By this combination a much more realistic impression of the objects can be derived.

Lasertracker

During the last years as a further advanced instrument set-up lasertrackers were introduced, which allow a continuous positioning or kinematic surveying of targets. In contrast to laserscanning here the laserbeam follows automatically a retroreflective target, which is used as handheld device in touch with a regular surface to determine a dense series of 3D-points as representatives for this surface. The distance changes are determined by interferometry, allowing high measuring frequencies and accuracies in the range of 0.05 mm. Just recently these instruments are equipped additionally with absolute distance devices, which allow in close range applications a similar high accuracy for the absolute distances

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as for the distance changes, reported by NIEMEIER & RIEDEL (2002), SCHWARZ (2002, 2003). MESSING (2002) presented a practical application of lasertracking in industry, where the form of pre-fabricated concrete elements is controlled very effectively by a lasertracker.

Automated total stations

Positioning with total stations nowadays means the inclusion of additional options, that came into wide use during this reporting period (e.g. DÜNISCH & KUHLMANN 2001, HENNES & KRICKEL 2000). The motorisation of the movements of the horizontal and vertical axis allow repeated observations for predefined setups, which makes the observations faster and more economic than classical approaches. The automatic target recognition "ATR" (SCHWARZ 2002, 2003) allows the use of these total stations for continuous monitoring. NIEMEIER et.al. (2000) have applied such a system for the continuous monitoring of a bridge with about 200 survey marks and 3 measuring epochs per day. The system is working now since more than three years.

A breakthrough was made in the development of distance observations without any targets, i.e. to carry out rapidly and precisely distance observations to natural objects. Main applications for these techniques is the documentation of buildings (BRUSCHKE 2002).

In STEMPFHUBER & MAURER (2001) a detailed analysis of the potential and characteristics of modern total stations is given. SCHWARZ (2001) reported on concepts and solutions for the calibration of this type of geodetic instruments in the laboratory.

Integration of GPS into existing networks

In the last four years the determination of heights by GPS was emphasized, while for the 2D-integration the concepts mainly were established earlier. Still the accuracy of GPS heights seems to be lower than the accuracy of geometric levelling, due to limiting factor of the lower atmosphere. Of special interest was the use of specific height reference surfaces. DENKER (2002) proposed the use of the nowadays available precise geoid/quasigeoid models with a stated precision of about 1 cm for distance up to 100km, which allow GPS-heighting without any passpoints and cm-accuracy, see also FELDMANN-WESTENDORFF (2002) for the application in Lower Saxony. The digital finite element height reference surface (DFHBF), as proposed by JÄGER & SCHNEID (2002), will be used for online GPS integration – again without further identical stations – in Baden-Württemberg (MEICHLE 2002).

Multi-Sensor-Systems (MMS)

In LÜCK et.al. (2001a) a combined DGPS/INS is used to determine irregularities of railway tracks, using the Sigma 30 INS of Sagem.

A completely new concept is the use of micro-mechanical MEMS inertial technology for indoor navigation (LÜCK et.al. 2001b), a future field for real-time positioning.

FOPPE (2001) has proposed the use of an inertial system for the determination of bending of structures, what is of special interest for bridges. He has developed a specific software concept, which allows to determine the relevant information more stable than common approaches and where he includes GPS-coordinates as additional information.

KATRYCZ (2002), KATRYCZ & NIEMEIER (2001) reported on the development of a strapdown inertial system, consisting of three ring laser gyros from Honeywell and three Qflex accelerometers from Allied Signal. A special housing was developed by Deutsche Montan Technologie (DMT), which fulfills the fireproof and the explosive-proof to make this IMS applicable in mining and in the interior of landfills.

The promising developments at the University of the Federal Armed Forces in Munich of multi-sensor-systems, named KiSS and MoSES for the determination of the trajectory of land vehicles and/or the geometry of streets or other transportation lines including its surrounding could be continued and applied in practise. In STERNBERG (2000) the status of this development is described in detail, while in STERNBERG et.al (1999) the filter algorithms for the raw data sets are outlined and in CASPARY et.al. (2000) the focus is set on the application for a complete survey of streets. In GRÄFE et.al. (2001) emphasis is laid on the use of the Applanix inertial system for the precision of the trajectory in the system MoSES. General aspects of kinematic surveying are outlined in CASPARY (2001).

A different MMS, consisting of GPS, azimuth and inclination sensors, is developed by THOMSEN & SCHALLER (2002) for the real-time monitoring and control of compaction processes on landfill sites. Here continuous information is used to derive a real-time DEM and to give steering information to the driver of the compaction machine, whether or not the compaction process is ready or further passing is required.

Applications to engineering

A special initiative is the development of an internet presentation on the potential and the high range of applications of engineering surveying, called CCES "Competence Centre of Engineering Surveying" (NIEMEIER et.al. 2002). This internet presentation is especially developed and designed for experts from neighboring disciplines. They get to know what is the actual standard of observation and processing techniques for their specific problem, what are proven measuring concepts and what can be achieved from the surveying profession during the different stages of the development of a project. Besides this information on regulations and codes will be made available and the CCES wants to stimulate the information exchange among scientists and practitioners from various professional fields. The internet presentation www.cces.de is established and maintained by the working committee "Engineering Surveying" of the DVW (German Society of Surveying, Geoinformation and Land Management). The acceptance of this web-page, which is partly available in English, is quite good with about 2000 visitors per week.

GRÜNDIG (1999) illustrates the tasks and the importance of engineering surveying for the structural engineers. A civil engineering's view on the importance of engineering surveying is given by LAERMANN (1999), who focused the potential that lies in a closer cooperation between both disciplines.

Kinematic positioning allows the use of real-time geometric information for guidance of construction machinery. Among others WUNDERLICH (2001) presented an overview on current achievements and future developments in this more and more important field of application for positioning systems.

References

- BACKHAUSEN D., BÄUMKER M., FITZEN H.-P.: Elimination von Mehrwegeeffekten und Antennenfehlern zur hochgenauen Erfassung von Bauwerksdeformationen mit GPS; *Vermessung und Raumordnung*, vol. 61, Dümmler, p 157-174, 1999
- BÄUMKER M., FITZEN H.-P., BACKHAUSEN D.: *Dreidimensionale permanente Überwachung der Eder-Talsperre mit GPS*; In: Schnädelbach/Schilcher (Eds.): *Ingenieurvermessung 2000*, Wittwer, p 155-165, 2000
- BORCHERS S., HEER R.: *Some results of deformation measurements with GOCA (GPS-based online control- and alarm-system) at Lock Uelzen*; Kahmen/Niemeier/Retscher (Eds.): *Geodesy for Geotechnical and Structural Engineering II*, p 38-50, 2002
- BRINGMANN O.: *Die Punktwolke aus Sicht der Mustererkennung*; In: Luhmann Th. (Ed.): *Photogrammetrie und Laserscanning*, Wichmann, p 99-104, 2002
- BRUSCHKE A.: *Tachymetrie zwischen Laserscanning und Photogrammetrie*; In: Luhmann Th. (Ed.): *Photogrammetrie und Laserscanning*, Wichmann, p 163-171, 2002
- CASPARY W.: *Kinematic Methods in Geodesy*; Proc. 4th Turkish-German Joint Geodetic Days; Berlin, 2001
- CASPARY W., HEISTER H., KLEMM J., STERNBERG H.: *Strassenaufnahme durch kinematische Vermessung*; In: Schnädelbach/Schilcher (Eds.): *Ingenieurvermessung 2000*, Wittwer, p 304-310, 2000
- DENKER H.: *Zur Nutzung von Geoidmodellen für die GPS-Höhenintegration*; In: Heck/Illner (Ed.): *GPS 2002: Antennen, Höhenbestimmungen und RTK-Anwendungen*, DVW Schriftenreihe 44, Wittwer, p 187-196, 2002
- DÜNISCH M., KUHLMANN H.: *Investigations of accuracy of tracking motorized tachymeters*; Proc. Optical 3D-Measurements, Vienna, 2001
- FOPPE K.: *Kombination von inertialen und satellitengestützten Beobachtungsverfahren zur ingenieurgeodätischen Überwachung von Brückenbauwerken*; *Wiss. Arb. Vermessungswesen Uni Hannover*, No. 242, Hannover
- FELDMANN-WESTENDORFF U.: *Zur hochgenauen Bestimmung von Normalhöhen mit GPS – Postprocessing und Echtzeitverfahren in der Landesvermessung Niedersachsen*; In: Heck/Illner (Ed.): *GPS 2002: Antennen, Höhenbestimmungen und RTK-Anwendungen*, DVW Schriftenreihe 44, Wittwer, p 224-246, 2002
- GRÄFE G., CASPARY W., HEISTER H., KLEMM J.: *The road acquisition system MoSES – determination and accuracy of trajectory data gained with Applanix POS/LV*; In: Proc. Int. Symp. on Mobile Mapping, Cairo, 2001
- GRÜNDIG L.: *Aufgaben und Bedeutung der Ingenieurvermessung im Bauwesen*; In: Klein (Ed.): *Ingenieurvermessung im Bauwesen*. DVW Schriftenreihe 36, Wittwer, p 9-23, 1999
- HEINZ I., METTENLEITNER M., FRÖHLICH C., STEPHAN A.: *Hochgeschwindigkeits-Laserscanner IMAGER 5003 für As-Built-Dokumentation*; In: Luhmann Th. (Ed.): *Photogrammetrie und Laserscanning*, Wichmann, p 73-83, 2002
- HENNES M., KRICKEL B.: *Zur Entwicklung von Untersuchungsverfahren zur Bestimmung der Leistungsfähigkeit von Robottachymetern*; *Flächenmanagement und Bodenordnung*, vol. 62, p 26-33, 2000
- HESSE CH.: *Deformation analysis of a shell structure under varying loads with Kalman-filter techniques*; Kahmen/Niemeier/Retscher (Eds.): *Geodesy for Geotechnical and Structural Engineering II*, p 92-100, 2002
- HOLLMANN R.: *Untersuchungen von GPS-Beobachtungen für kleinräumige geodätische Netze*; *Schrift. Geodäsie Uni BW*, Neubiberg, 341 p, 2000
- HOVENBITZER M.: *Zur Automation berührungsloser 3D-Objekterfassung im Nahbereich*; Diss. TH Darmstadt, 2001
- ILLNER M.: *RTK-Messungen für genaue Ingenieuranwendungen*; In: Heck/Illner (Ed.): *GPS 2002: Antennen, Höhenbestimmungen und RTK-Anwendungen*, DVW Schriftenreihe 44, Wittwer, p 47-64, 2002
- JÄGER R., SCHNEID S.: *Passpunktfreie direkte Höhenbestimmung mittels DFHBF – ein Konzept für Positionierungsdienste wie SAPOS*; 4. SAPOS-Symposium, Hannover, p 149-166, 2002
- KÄLBER S., JÄGER R.: *Realisierung eines GPS-basierten Online Kontroll- und Alarmsystems (GOCA) und Diskussion adäquater geometrischer und systemanalytischer Ansätze zum online Monitoring im Talsperrenbereich*; In: *Wasserwirtschaft* vol. 91, p 84-89, 2001
- KATRYCZ W.: *A strapdown inertial measurement system for the monitoring of drainage pipes in landfill sites*; Kahmen/Niemeier/Retscher (Eds.): *Geodesy for Geotechnical and Structural Engineering II*, p 344-354, 2002
- KATRYCZ W., NIEMEIER W.: *On methodological aspects of system development in high precision inertial pipe surveying*; In: Proc. KiSS-Symposium, Banff, 2001
- KERN F.: *Automatische Modellierung von Bauwerksgeometrien aus 3D-Laserscanner-Daten*; *Geodätische Schriftenreihe TU Braunschweig*, Heft 19, 152 pp, 2003
- KERN F., THOMSEN S., MITTELSTÄDT D., GAY O.: *Integrierte Auswertung von Laserscanner- und Bilddaten für das Facility Management*; In: Luhmann Th. (Ed.): *Photogrammetrie und Laserscanning*, Wichmann, p 107-117, 2002
- KÖNIG R., BAUER T., BLEY M.: *3D-Laserscanning historischer Gebäude*; In: Luhmann Th. (Ed.): *Photogrammetrie und Laserscanning*, Wichmann, p 128-132, 2002
- KORITTKEN N., PALTE G.: *Real-Time-Monitoring von bergbaubedingten Gebäudebewegungen*; In: Schwarz W. (Ed.): *Interdisziplinäre Messaufgaben im Bauwesen*, DVW Schriftenreihe 43, Wittwer, p 183-195, 2002
- KRAUSE U.: *Brückenbauwerke im Rahmen der Öresundverbindung*; In: Schnädelbach/Schilcher (Eds.): *Ingenieurvermessung 2000*, Wittwer, p 75-87, 2000
- KUHLMANN H.: *Investigation of new measurement techniques for bridge monitoring*; Kahmen/Niemeier/Retscher (Eds.): *Geodesy for Geotechnical and Structural Engineering II*, p 123-132, 2002

- LAERMANN K.-H.: *Beitrag der Ingenieurvermessung zur Sicherheitsbeurteilung von Baukonstruktionen – Perspektiven einer Kooperation*; In: Klein (Ed.): *Ingenieurvermessung im Bauwesen*. DVW Schriftenreihe 36, Wittwer, p 166-182, 1999
- LÜCK T., EISSFELLER B., KREYE C., MEINKE P.: *Measurement of line characteristics and of track irregularities by DGPS and INS*. In: Proc. KiSS, Banff, 2001a
- LÜCK T., KREYE C., EISSFELLER B.: *Status and indoor use of MEMS inertial technology*. In: DGON Symp. Indoor Navigation, Munich, p. 73-99, 2001b
- MEICHLE H.: *Passpunktfreie direkte Höhenbestimmung mittels DFHBF in Baden-Württemberg*; In: Heck/Illner (Ed.): *GPS 2002: Antennen, Höhenbestimmungen und RTK-Anwendungen*, DVW Schriftenreihe 44, Wittwer, p 197-223, 2002
- MESSING M.: *Lasertracker für die Vermessung von Tübbingern*; In: Schwarz W.(Ed.): *Interdisziplinäre Messaufgaben im Bauwesen*, DVW Schriftenreihe 43, Wittwer, p 87-102, 2002
- MÖSER M., NEUMANN G.: *Automatisierte Tachymeter für das Monitoring*; In: Schwarz W.(Ed.): *Interdisziplinäre Messaufgaben im Bauwesen*, DVW Schriftenreihe 43, Wittwer, p 69-86, 2002
- MUCKE J.: *Zur Leistungsfähigkeit des Lasermesssystems Callidus*; In: Luhmann Th. (Ed.): *Photogrammetrie und Laserscanning*, Wichmann, p 84-92, 2002
- NIEBUHR E.: *3D object reconstruction using the Callidus technology*; Kahmen/Niemeier/Retscher (Eds.): *Geodesy for Geotechnical and Structural Engineering II*, p 394-395, 2002
- NIEMEIER W., BACKHAUSEN D., HÖPER D., NEHRKAMP K.-H., PETERSEN M., SCHÄFER M., STOLLENWERK H.-J.: *CCES – Competence Centre for engineering surveying – A new internet service promoting the surveying engineering profession*; Kahmen/Niemeier/Retscher (Eds.): *Geodesy for Geotechnical and Structural Engineering II*, p 195-200, 2002
- NIEMEIER W., KERN F.: *Anwendung von scannenden Messverfahren*; In: Proc. „Vom Handaufmass bis High Tech“, BTU Cottbus, p 134-140, 2001
- NIEMEIER W., KRAUS B., MIIMA J.-B., RIEDEL B., FLEBBE H.: *Bestimmung von 3D-Verformungen einer Brücke mit motorisierten Tachymetern*; In: Schnädelbach/Schilcher (Eds.): *Ingenieurvermessung 2000*, Wittwer, p 122- 132, 2000
- NIEMEIER W., RIEDEL B.: *Photogrammetrische Objekterfassung zur Bestimmung der Oberflächengeometrie*; VDI-Tagung PUR 2002, Bad Neuenahr, p 245-260, 2002
- NIEMEIER W., THOMSEN S., SCHÄFER M.: *3D-Geometrieerfassung mit terrestrischen Laserscannern*; In: Luhmann Th. (Ed.): *Photogrammetrie und Laserscanning*, Wichmann, p 15-26, 2002b
- RUNNE H., NIEMEIER W., KERN F.: *Application of laser scanners to determine the geometry of buildings*; Proc. Optical 3D-Measurements, Vienna, p 41-48, 2001
- SCHÄFER M., WEITHE G.: *Survey solution on the construction sites North Downs Tunnel and Medway Crossing Bridge – high speed railway from London to the Eurotunnel*; Kahmen/Niemeier/Retscher (Eds.): *Geodesy for Geotechnical and Structural Engineering II*, p 156-167, 2002
- SCHOCK T.: *Cyrax 3D-Laserscanning – Lösungen im Anlagenbau und Vermessungswesen*; In: Luhmann Th. (Ed.): *Photogrammetrie und Laserscanning*, Wichmann, p 93-98, 2002
- SCHWARZ W.: *Geodätische Laborkalibrierung – Stand der Technik*; In: Heister/Staiger (Ed.): *Qualitätsmanagement in der geodätischen Messtechnik*. DVW Schriftenreihe 42, Wittwer, p. 44-69, 2001
- SCHWARZ W.: *Geodätische Messverfahren für das Bauwesen*; In: Schwarz W.(Ed.): *Interdisziplinäre Messaufgaben im Bauwesen*, DVW Schriftenreihe 43, Wittwer, p 23-42, 2002
- SCHWARZ W.: *Moderne Sensorik für die Ingenieurgeodäsie*; In: Proc. „Ingenieurgeodäsie 2003“, TU Graz, 2003
- SCHWEMANN R., EFFKEMANN C.: *Kombiniertes Monoplotting in Laserscanner- und Bilddaten mit Phidias*; In: Luhmann Th. (Ed.): *Photogrammetrie und Laserscanning*, Wichmann, p 57-70, 2002
- STAIGER R., MÜHL A.: *Der Einsatz des Laserscanners im Stahlwerk*; In: Luhmann Th. (Ed.): *Photogrammetrie und Laserscanning*, Wichmann, p 118-127, 2002
- STEMPFHUBER W., MAURER W.: *Leistungsmerkmale von zielverfolgenden Tachymetern bei dynamischen Applikationen*; In: Heister/Staiger (Ed.): *Qualitätsmanagement in der geodätischen Messtechnik*. DVW Schriftenreihe 42, Wittwer, p. 189-206, 2001
- STEPHAN A., HEINZ I., METTENLEITNER M., HÄRTL F., FRÖHLICH C., DALTON G., HINES D.: *Laser sensor for as-built documentation*; Kahmen/Niemeier/Retscher (Eds.): *Geodesy for Geotechnical and Structural Engineering II*, p 396-403, 2002
- STERNBERG H., CASPARY W., HEISTER H.: *Filteralgorithms for optimal determination of position and attitude of mobile mapping system KiSS*; Proc. Int. Workshop on Mobile Mapping, Bangkok, Thailand, p 221-226, 1999
- STERNBERG H.: *Zur Bestimmung der Trajektorie von Landfahrzeugen mit einem hybriden Messsystem*; *Schriftenreihe Vermessungswesen*, UniBW, Neubiberg, 2000
- THOMSEN S., SCHALLER M-B: *A multi-sensor system for real-time monitoring and control of emplacement processes on landfill sites*; Kahmen/Niemeier/Retscher (Eds.): *Geodesy for Geotechnical and Structural Engineering II*, p 257-265, 2002
- WEHR A.: *Laserscanner in der Bauaufnahme*; Proc. „Vom Handaufmass bis High Tech“, BTU Cottbus, 2000
- WÜBBELMANN H.: *Hydrostatic monitoring of buildings with ultrasonic techniques*; Kahmen/Niemeier/Retscher (Eds.): *Geodesy for Geotechnical and Structural Engineering II*, p 355-362, 2002
- WUNDERLICH T.: *Machine Guidance – Current achievements and future developments*; In: Proc Int. Symp. On Mobile Mapping, Cairo, 2001

Nuisance effects in precise GPS positioning

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Introduction

Within the GPS error budget the most important influences as seen today are the

- antenna phase center variation (PCV)
- multipath
- tropospheric and ionospheric propagation delays.

Other important aspects include the reliability of ambiguity resolution and the time needed to fix the ambiguities.

Multipath and PCV are station dependent effects; they are dealt with in station calibration procedures. Tropospheric and ionospheric propagation delays can be reduced by relative GPS observations. The residual effects are distance dependent. The same holds for most ambiguity resolution techniques. In permanent reference networks real-time error modeling can be offered to mitigate the effects in precise relative positioning with mobile GPS equipment.

During the past four years a considerable amount of research work in this area has been carried out in Germany. A selection of key publications is given in the text. A more extensive list is included in the references.

Antenna phase center variations

Absolute and relative calibration techniques of GPS antennas comprise a wide field of activities (GÖRRES 2001, WANNINGER 2002). Now it is common understanding that in reference station networks, such as the networks of the *International GPS Service* (IGS) and the *Satellite Positioning Service of the German State Surveying Agencies* (SAPOS), as well as for higher precision surveying tasks, only calibrated antennas should be used. Powerful methods of absolute calibration have been developed. Besides calibration in anechoic chambers (BECKER, ZEIDLER, 2002) a new method of absolute field calibration using a robot has been developed (MENGE et al., 1998; WÜBBENA et al., 2000; BÖDER et al. 2001; SCHMITZ et al. 2002a). For most antenna types representative results are now available (SCHMITZ et al. 2002b). Attempts are being made to define a “zero antenna” (without PCV) for use in reference station networks. The great importance of this topic is emphasized by the fact that four “GPS antenna-workshops” have been organized at the universities of Bonn and Hannover between 1998 and 2002. One highlight of the last workshop 2002 in Hannover was

the presentation of results from an intercomparison of calibration values for a set of five antennas obtained by different groups with different methods. The preliminary results show that there is agreement on the level of the PCV-patterns of 1 to 4 mm depending on the antenna type and frequency (CAMPBELL, SEEGER 2002, ROTHACHER, SCHMID 2002a).

The use of absolute antenna calibration in global networks has created a scale problem with respect to the other space techniques and is probably related to the lack of a correct antenna model for the GPS satellites (ROTHACHER 2001, ROTHACHER, SCHMID 2002b).

Multipath mitigation

The traditional techniques of multipath mitigation are signal processing techniques in the receiver (e.g. narrow correlator) or particular antenna design (e.g. choke ring antenna). An alternative approach for permanent stations is multipath calibration. A new technique has been developed using a robot and absolutely calibrated antennas. The basic idea is to decorrelate the multipath through controlled motion of a robot operating near a station to be calibrated. First results are reported in BÖDER (2002). The use of permanent reference station network observations for the localization and calibration of multipath is described by WANNINGER et al. (2001).

Another station dependent nuisance effect is diffraction (bending of the signal path). Its effects are felt when the direct GPS signal is obstructed but a diffracted signal is received. GPS signal diffraction may cause errors of up to several centimeters (WANNINGER et al., 2000).

Tropospheric propagation delay

The increasing number of permanent GPS stations (e.g. IGS, SAPOS), and the availability of GPS receivers on *Low Earth Orbiters* (LEO) continuously provides a wealth of data for atmospheric delay modeling. Special approaches apply an integration of numerical weather models (SCHÜLER, 2001). Radiometric measurements can be used for validation studies (BECKER et al., 2002). Residual tropospheric errors can be modeled in active reference networks (WANNINGER, 2000) within the concept of VRS (virtual reference stations) or ACP (area correction parameters). Selected studies refer

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to the tropospheric effect on vertical positioning (DEPENTHAL et al., 2000)

Ionospheric propagation delay

Like the troposphere also the ionosphere can be modeled by the available wealth of data from ground tracking stations and LEO occultations (KLEUSBERG, 1998). Severe ionospheric conditions were experienced during the recent years of solar maximum. Various studies have been performed on how these effects can be mitigated by the use of permanent reference station networks (WANNINGER, 1999). New aspects arise with the availability of additional frequencies using the forthcoming Galileo system (PANY et al., 2002).

Ambiguity resolution techniques

Significant progress has been achieved in ambiguity resolution techniques by a more complete modeling of GPS observations (WÜBBENA, 2001). Particular investigation improves the techniques (GRAFAREND, 2000). Emphasis is given to near real-time solutions (KUTTERER, 2000). A powerful procedure uses data from permanent reference stations for an error modelling in real-time (WANNINGER, 2000). This technique reduces distance dependent errors (orbit, troposphere, ionosphere) and at the same time it reduces the time to fix ambiguities and increases the success rate of ambiguity fixing. In Germany this concept is widely used in the SAPOS service (AdV, 2002). A modern approach is the modelling of the error state within a regional network of reference stations (WÜBBENA et al., 2001) and the integration with continental and global networks (WÜBBENA, 2002b). Further advantages are expected by the inclusion of additional GPS signals (VOLLATH et al., 1999) or Galileo data (TIBERIUS et al., 2002).

Integrated modelling of effects

The domination of station dependent and distance dependent nuisance effects is intensively treated in permanent reference station networks. The procedures in use are station calibration, virtual reference stations (VRS) and area correction parameters (ACP). Comprehensive publications can be taken from the proceedings of the annual SAPOS conferences, for example AdV (2002). Some key publications in this area are BÖDER et al. (1999), WANNINGER (2000), WÜBBENA (2002a).

The capacities and limits of nuisance effect modeling are demonstrated in a comprehensive intercomparison study. The overall effect in a data analysis can be considered as a process noise, including software noise (selection of a particular software package), operator noise (selection of particular options), reference frame realization noise (selection of a set of fiducials). As a consequence, a given data set will lead to slightly different results, when different operators work with different software packages. A 40-day long data set from about 50 stations on the southern hemisphere have been analysed with 4 different software packages in 7 laboratories. The mean differences between solutions are 1 cm in horizontal position and 2 cm in height (DIETRICH et al., 2001).

References

- AdV: *Vorträge des 4. SAPOS Symposiums, 21.-23. Mai 2002 in Hannover*. Arbeitsgemeinschaft der Vermessungsverwaltungen der Länder der Bundesrepublik Deutschland, 2002
- AUGATH, W.: *Signal and Station Validation of GNSS Permanent Stations for Precise Positioning, Weather Forecast and Navigation*. 5th Setmana Geomatica, Cartography, Telematics and Navigation. Barcelona. 11.-14.02.2003.
- AUGATH, W., BLUMENBACH, TH., WILDT, ST.: *SAPOS 2002 Symposium: Qualitätssicherung bei Referenzstationen und in Referenzstationsnetzen*. SAPOS-Symposium 2002, Hannover, 21.-23.05.2002.
- BECKER M., HAEFELE P., PESEC P.: *First Results of WVR1100 Water Vapor Radiometer Measurements in Graz and the CERGOP-2 Project*; Proceedings WEGENER 2002, Athens, June 12-14, 2002, NTUA Athens, Greece.
- BECKER M., ZEIDLER C.: *GPS Antenneneichung in der Absorbierhalle des EMV Testzentrums Greding*, Proc., 4. GPS-Antennenworkshop, Hannover, 21. Mai 2002, LGN 2002.
- BÖDER V., MENGE F.: *Kalibrierung von GPS-Referenzstationen*; 2. SAPOS-Symposium, Berlin 1999
- BÖDER V., MENGE F., SEEBER G., WÜBBENA G., SCHMITZ M.: *How to Deal With Station Dependent Errors – New Developments of the Absolute Calibration of PCV and Phase-Multipath With a Precise Robot*; Proceedings of the 14th International technical Meeting of the Satellite Division of the Institute of Navigation ION GPS 2001, Salt Lake City 2001
- BÖDER V.: *Zur hochpräzisen GPS-Positions- und Lagebestimmung unter besonderer Berücksichtigung mariner Anwendungen*. Wiss. Arbeiten der Fachrichtung Vermessungswesen der Universität Hannover, Nr. 245, 2002
- CAMPBELL J., SEEBER G.: 4. *GPS-Antennenworkshop am 21. Mai 2002 im Rahmen des 4. SAPOS-Symposiums in Hannover*. Zeitschrift für Geodäsie, Geoinformation und Landmanagement (zfv) 128 (2002), 335, Proceedings of the Workshop available at www.lgn.de
- DEPENTHAL C., MAYER M., KUTTERER H., LINDNER K., HECK B.: *Einfluss der Atmosphäre auf GPS-Beobachtungen im Bereich der Antarktis*; in: Dietrich R. (Ed.): *Deutsche Beiträge zu GPS-Kampagnen des Scientific Committee on Antarctic Research (SCAR) 1995-1998*. DGK B 310, München 2000, 195-199
- DIETRICH R., DACH R., ENGELHARDT G., IHDE J., KORTH W., KUTTERER H.-J., LINDNER K., MAYER M., MENGE F., MILLER H., MÜLLER C., NIEMEIER W., PERLT J., POHL M., SALBACH H., SCHENKE H.-W., SCHÖNE T., SEEBER G., VEIT A., VÖLKSEN C.: *ITRF coordinates and plate velocities from repeated GPS campaigns in Antarctica – an analysis based on different individual solutions*; Journal of Geodesy, 74, 756-766, 2001
- EISSFELLER B., TIBERIUS C., PANY T., BIBERGER R., SCHÜLER T., HEINRICHS G.: *Instantaneous Ambiguity Resolution for GPS/Galileo RTK Positioning*; Proceedings of the 9th Saint Petersburg International Conference on Integrated Navigation Systems, Russia, St. Petersburg, 27-29
- GÖRRES, B.: *Kalibrierung von GPS-Antennen*. VDV-Schriftenreihe, Band 19 "GPS-Referenzstationsdienste", Verlag Chmielorz GmbH, Wiesbaden 2001, 31-46
- GRAFAREND E.W.: *Mixed integer-real valued adjustment (IRA) problems: GPS initial cycle ambiguity resolution by means of the LLL algorithm*; GPS Solutions 4 (2000) 31-44

- GRAFAREND E.W., SHAN J.: *GPS solutions: closed forms, critical and special configurations of P4P*; GPS Solutions 5 (2002) 29-41
- HOWIND J., KUTTERER H., HECK B.: *Impact of temporal correlations on GPS-derived relative point positions*; Journal of Geodesy, 73 (1999), 246-258
- HOWIND J., BÖHRINGER M., MAYER M., KUTTERER H., LINDNER K., HECK B.: *Korrelationsstudien bei GPS-Phasenbeobachtungen*; in: Dietrich R. (Ed.): Deutsche Beiträge zu GPS-Kampagnen des Scientific Committee on Antarctic Research (SCAR) 1995-1998. DGK B 310, München 2000, 201-205
- KLEUSBERG A.: *Atmospheric Models from GPS*; in: Teunissen, Kleusberg, GPS for Geodesy, 2nd edition, chpt. 15, 1998
- KUTTERER H.: *On the Precision and Reliability of Near Real-Time GPS Phase Observation Ambiguities*; in: Schwarz, K.-P. (Ed.): Geodesy beyond 2000. Springer, Berlin/Heidelberg 2000, 249-254
- MENGE F., SEEBER G., VÖLKSEN C., WÜBBENA G., SCHMITZ M.: *Results of Absolute Field Calibration of GPS Antenna PCV*; in: Proceedings of the 11th International Technical Meeting of the Satellite Division of the Institute of Navigation ION GPS-98, September 1998
- MENGE F., SEEBER G.: *Untersuchungen und Beiträge zur Problematik der Phasenzentrumsvariationen von GPS-Antennen*; Deutsche Geodätische Kommission, Reihe B, Heft 310, 2000
- PANY T., EISSFELLER B., WINKEL J.: *Analysis of the Ionospheric Influence on Signal Propagation and Tracking of Binary Offset Carrier (BOC) Signals For Galileo And GPS*; Proc. of the 27 General Assembly of the International Union of Radio Science, Maastricht, August, 2002
- ROTHACHER M.: *Comparison of absolute and relative antenna phase center variations*; GPS solutions 4(4), 55-60, 2001
- ROTHACHER M., SCHMID R.: *Aktueller Stand zur Antennenkalibrierung beim IGS*; 4. GPS Antennenworkshop, Hannover, Mai 2002a
- ROTHACHER, M., SCHMID R.: *GPS-Antennenkalibrierungen aus nationaler und internationaler Sicht*. 4. SAPOS-Symposium, 21.23. Mai 2002, Hannover, LGN Hannover, 124-131, 2002b
- SCHMITZ M., WÜBBENA G., BOETTCHER G., SEEBER G., BÖDER V., MENGE F.: *Absolute Receiver Antenna Calibration with a Robot*; IGS Workshop "Towards Real-Time", Ottawa, Canada 2002a
- SCHMITZ M., WÜBBENA G., BOETTCHER G.: *Test of phase center variations of various GPS antennas, and some results*; GPS Solutions, Vol. 6, number 1-2, 2002b
- SCHÜLER T., HEIN G.W., EISSFELLER B.: *GNSS Zenith Wet Delay Estimation Considering Their Stochastic Properties*; Proceedings of GNSS '99, 3rd European Symposium, Genoa, Italy, Oct. 5-8, 1999
- SCHÜLER T., HEIN G.W.: *Improved Tropospheric Delay Modeling Using an Integrated Approach of Numerical Weather Models and GPS*; Proceedings of ION GPS 2000, The Institute of Navigation, Salt Lake City, Utah, USA, 19-22 September 2000
- SCHÜLER T., HEIN G.W., EISSFELLER B.: *Towards an Optimal Strategy for GPS Wet Delay Kalman Filtering*; Proceedings of IAIN 2000/ION Annual Meeting, San Diego, Catamaran Hotel, 26-28 June 2000
- SCHÜLER T., HEIN G.W., EISSFELLER B.: *On the Use of Numerical Weather Fields for Troposphere Delay Estimation in Wide Area Augmentation Systems*; Proceedings of GNSS 2000, Royal Institute of Navigation, Edinburgh, Scotland, May 1-4, 2000
- SCHÜLER T.: *On Ground-Based GPS Tropospheric Delay Estimation*; Dissertation, Schriftenreihe 73, Studiengang Geodäsie und Geoinformation, Universität der Bundeswehr München, February 2001
- SCHÜLER T., HEIN G.W., EISSFELLER B.: *Tropospheric Delay Prediction in Wide Area Augmentation Systems Using Numerical Weather Fields*; Proceedings of KIS 2001, Banff, Alberta, Canada, June 5-8, 2001
- SCHÜLER T., HEIN G.W., EISSFELLER B.: *A New Tropospheric Correction Model for GNSS Navigation*; Proceedings of GNSS 2001, V GNSS International Symposium, Spanish Institute of Navigation, Seville, Spain, May 8-11, 2001
- SCHÜLER T., HEIN G.W.: *Tropospheric Correction Services for GNSS Users – Concepts, Status and Future Prospects*; Proceedings of GNSS 2002 – Global Navigation Satellite Systems, Copenhagen, Denmark, May 27-30, 2002
- TIBERIUS C., PANY T., EISSFELLER B., JOOSTEN P., VERHAGEN S.: *0.99999999 confidence ambiguity resolution with GPS and Galileo*; GPS Solutions 6, 2002, pp. 96-99.
- VÖLKSEN C., MENGE F.: *The impact of different GPS antenna calibration models on the computations in the EUREF Permanent Network*; Proceedings of the Symposium of the IAG Subcommittee for Europe for Europe (EUREF), Ponta Delgada, Portugal 2002
- VOLLATH U., BIRNBACH S., LANDAU H., FRAILE-ORDONEZ J.M., MARTIN-NEIRA, M.: *Analysis of three-carrier ambiguity resolution technique for precise relative positioning in GNSS-2*; Navigation, 46 (1999):13-23
- VOLLATH U., BUECHERL A., LANDAU H., PAGELS C., WAGNER B.: *Long-Range RTK Positioning Using Virtual Reference Stations*; Proceedings of ION GPS 2000, Salt Lake City (2000), 1143-1147
- VOLLATH U., LANDAU H., CHEN X., DOUCET K., PAGELS C.: *Network RTK Versus Single Base RTK – Understanding the Error Characteristics*; Proceedings of ION GPS 2002, Portland (2002), 2774-2781
- WANNINGER L.: *The Performance of Virtual Reference Stations in Active Geodetic GPS- networks under Solar Maximum Conditions*; Proceedings of ION GPS '99, Nashville (1999), 1419-1427.
- WANNINGER L.: *Präzise Positionierung in regionalen GPS-Referenzstationsnetzen*; Habilitationsschrift, Deutsche Geodätische Kommission Reihe C, Heft 508, München 2000, 68pp.
- WANNINGER L., FREVERT V., WILDT S.: *Der Einfluss der Signalbeugung auf die präzise Positionierung mit GPS*, Zeitschrift für Vermessungswesen, 125 (2000):8-16
- WANNINGER L., MAY M.: *Carrier Phase Multipath Calibration of GPS Reference Stations*; Navigation (Journal of the Institute of Navigation, Washington), 48 (2001):113-124
- WANNINGER L.: *Möglichkeiten und Grenzen der relativen GPS-Antennenkalibrierung*. Zeitschrift für Geodäsie, Geoinformation und Landmanagement (zfv), 127 (2002):51-58
- WANNINGER L.: *Virtual Reference Stations for Centimeter-Level Kinematic Positioning*; Proceedings of ION GPS 2002, Portland (2002), 1400-1407

- WÜBBENA G., SCHMITZ M., MENGE F., BÖDER V., SEEBER G.: *Automated Absolute Field Calibration of GPS Antennas in Real-Time*; Proceedings of the 13th International Technical Meeting of the Satellite Division of the Institute of Navigation ION GPS 2000, Salt Lake City
- WÜBBENA G.: *Zur Modellierung von GNSS-Beobachtungen für die hochgenaue Positionsbestimmung*; in: Festschrift Prof. G. Seeber zum 60. Geburtstag, Wiss. Arbeiten Fachrichtung Vermessungswesen an der Universität Hannover, Nr. 239, 2001
- WÜBBENA G., WILLGALIS S.: *State Space Approach for Precise Real Time Positioning in GPS Reference Networks*; International Symposium on Kinematic Systems in Geodesy, Geomatics and Navigation, KIS-01, Banff, Canada 2001
- WÜBBENA G., SCHMITZ M., BACHMANN M., SEEBER G., BÖDER V. MENGE F.: *Zur absoluten Kalibrierung von Referenzstationen: Grundlagen, Anwendungen und das Hannoversche Verfahren*; GPS-Antennenworkshop Hannover, 21. Mai 2002a
- WÜBBENA G.: *Zur großräumigen Vernetzung von GNSS-Referenzstationen*. 4. SAPOS-Symposium Hannover 2002b

Additional bibliography made available after completion of the reports to Section I

- BOCK H., BEUTLER G., SCHAER S., SPRINGER T.A., ROTHACHER M.: *Processing Aspects Related to Permanent GPS Arrays*, Earth Planets Space, Vol. 52, 10657-662, Terrapub, Tokyo, 2000
- ROTHACHER M.: *Estimation of station heights with GPS*, IAG Symposium: Vertical Reference Systems, Vol. 142, 81-90, Springer, Berlin/Heidelberg, 2002
- HABRICH H., GURTNER W., ROTHACHER M.: *Double Difference Ambiguity Resolution for GLONASS/GPS Carrier Phase*, Proceedings of the 12-th International Technical Meeting of ION GPS'99, Nashville September 14-17, 1609-1618, 1999
- ROTHACHER M.: *Bestimmung von Variationen der Antennenphasenzentren mit GPS-Beobachtungen: Vergleiche und Kombination*, Proceedings des Workshop Festlegung des Phasenzentrums von GPS-Antennen, Bonn, 28.4.1999, Geodätisches Institut Bonn, Bonn, 1999
- ROTHACHER M.: *Phasenzentrumsvariationen: Regionale und globale Aspekte*, GPS-Antennenworkshop 2000, Institut für Erdmessung, Universität Hannover, Hannover, 2000
- ROTHACHER M., SCHAER S.: *Estimation of Troposphere Gradients in Global GPS Solutions*, Eos, Transactions, American Geophysical Union 2000 Fall Meeting, Vol. 81, 48F334, San Francisco, 2000
- ROTHACHER M., MADER G.: *Receiver and Satellite Antenna Phase Center Offsets and Variations*, Position Paper of the "Antenna Session", 2001
- ROTHACHER M.: *Kombination absoluter und relativer Antennenkalibrierungen*, 3. GPS-Antennen-Workshop, 52-87, Geodätisches Institut der Rheinischen Friedrich-Wilhelms-Universität Bonn, Bonn, 2001
- ROTHACHER M., REITBERGER J.: *Absolute and Relative GPS Antenna Phase Center Variations: New Developments*, Geophysical Research Abstracts: 26th EGS General Assembly, Vol. 3, Nice, 2001
- ROTHACHER M., MADER G.: *Receiver and Satellite Antenna Phase Center Offsets and Variations*, Position Paper of the "Antenna Session", IGS Workshop in Ottawa, 2002
- SCHMID R., ROTHACHER M.: *Estimation of Elevation-Dependent GPS Satellite Antenna Phase Center Variations*, Geophysical Research Abstracts: 27th EGS General Assembly, Vol. 4, Nice, 2002
- SCHMID R., ROTHACHER M.: *Estimation of Satellite Antenna Phase Center Variations*, IGS-Workshop 2002, Ottawa, 2002
- SCHMID R., ROTHACHER M.: *Ergebnisse und Analyse des Vergleichstests von Kalibrierungsverfahren für GPS-Antennen*, 4. GPS-Antennenworkshop, Hannover, 2002

SECTION II

ADVANCED SPACE TECHNOLOGY

Advanced Space Technology – Overview and highlights –

R. RUMMEL¹

The past four years were unusually active and successful in the area of geodetic space research and our expectation is that this will hold for the next four years, too. The activities can be divided into three categories: (1) Efforts to improve the consistency and precision of existing geodetic space techniques in space and time, (2) the extension of existing techniques into new fields of applications and (3) the initiation, realization and preparation of new satellite missions. Very helpful in these efforts proved the support of the German Research Foundation (DFG) and the support of the German Ministry of Research and Technology (BMFT). The latter initiated a so-called geo-technology programme. One of its twelve themes is called “Observation of System Earth from Space”, a topic focussing of Earth oriented geodetic space research.

In the following the above three categories of geodetic space research activity shall be summarized.

Towards an Integrated Global Geodetic Observing System (IGGOS).

The progress of geodetic space research has lead to many new developments in Earth sciences. While in the past geodesy has mainly contributed to geodynamics, it has nowadays expanded into glaciology, oceanography, weather prediction, climate research and even hydrology. There is general agreement, however, that the geodetic contribution to global change and Earth system research could be strengthened by closer tying together its three fundamental pillars earth rotation, geo-kinematics and gravity/geoid to one integrated system. This would require the integration of these three basic entities to one global reference frame and the maintenance of its stability and consistency in space and time over decades at a precision level of 10^{-9} or better. Apart from its scientific value such a system would also improve geodesy’s visibility in the context of all other Earth science disciplines. An international discussion with the aim to create such an observing system has been initiated with a symposium “Towards a Global Integrated Geodynamic Observing System” that was held in Munich in October 1998, (RUMMEL et al., 1998). Meanwhile IAG established a working group that formulated a program for such an initiative. The plan is to implement IGGOS as an IAG project in 2003 in Sapporo. Already now several international and national research programs take IGGOS into consideration.

A precondition for any establishment of a global geodetic observing system is the integration and combination of all existing geodetic space techniques with an accuracy, consistency and reliability higher than what is available today. This is currently one of the central objectives of the International Earth Rotation Service (IERS), compare (DICK and RICHTER, 2002 and <http://www.iers.org/iers/>). On its working agenda are therefore items such as the direct comparison of space techniques, unification of processing methods in terms of datum definition, adjustment approaches and auxiliary geophysical models, and improvement of local ties. In a coordinated effort of GeoForschungsZentrum (GFZ) and of Forschungsgruppe Satellitengeodäsie (FGS) the German level of engagement in IERS-activities has been increased significantly. The Bundesamt für Kartographie und Geodäsie (BKG) took responsibility of the IERS-central bureau, the Satellite Geodetic Research Facility (FESG) of Technical University Munich coordinates the analysis activities inside IERS (<http://alpha.fesg.tu-muenchen.de/~iers/>), the German Geodetic Research Institute (DGFI), the Geodetic Institute of University of Bonn (GIUB) and GFZ act as combination research centres.

An important contribution to the international effort of improving the global distribution of observing stations, in general, and of fundamental stations, in particular, has been taken. Of special importance are the refurbishment of the VLBI-telescope in O’Higgins, Antarctica and the installation of the transportable fundamental station TIGO in Conception, Chile. The latter is operated in close cooperation with our colleagues from Chile. Regular observation sessions of the various systems started in spring 2003.

Expansion of geodetic space techniques into new fields of Earth sciences.

GPS continues to remain a never ending success story. Originally used in geodesy for high precision relative positioning it is meanwhile a standard technique for crustal motion monitoring, Earth rotation determination, kinematic positioning and time comparison and transfer. In recent years it became, in addition, almost a standard for precise orbit determination of low orbiting satellites, again with a large number of secondary uses and, last not least, it turned into a very powerful tool for probing the atmosphere (ionosphere, troposphere, space weather). The latter adds atmospheric sounding as a forth pillar to the classical geodetic trinity Earth rotation, geo-kinematics and gravity & geoid. It is an

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example where a traditional noise source of geodetic measurements, namely atmospheric refraction, could be turned into a highly valuable signal. The principal fields of application are monitoring of the ionosphere and the determination of profiles of atmospheric refractivity. The latter are reconstructed from the bending angles of signal profiles of rising and setting GPS satellites. In dry air they can be translated directly into density profiles, and introducing some model assumptions, into pressure and temperature profiles. More complicated is the separation into humidity and temperature when there is water vapor present. But there is a clear potential for obtaining high quality water vapor profiles with this approach. See (REIGBER et al., 2003).

The alternative but complementary approaches are atmospheric sounding based on a ground network of permanent GPS receivers (and meteorological stations) or on limb sounding from a low Earth orbiter (LEO) to the satellites of the GPS. In Germany both methods are applied. There exists a ground based network operated by GFZ and supported by the receiver network SAPOS of the German federal surveying agencies and by BKG. On the other hand

there is the very successful space-borne experiment running with CHAMP.

A very interesting technological development is InSAR. It matured from an experimental technique to an operational one with many applications in Earth sciences. It adds a very powerful technique to the determination of the geometrical shape of land surfaces and of their change with time and it has to become an intrinsic part of the global observing system strategy. With InSAR the dividing line between geodetic positioning, remote sensing and photogrammetry has vanished. Very likely this will contribute to a closer cooperation of these communities for the benefit of Earth sciences.

New space missions and techniques.

Undoubtedly the most spectacular development is the large number of geodetic space mission that emerged during the past four years. Several of these missions have been realized with significant support from the Federal Republic of Germany, either as part of national programs or through Germanys ESA membership. Table 1 gives an overview of these missions, these with significant German (G) contributions or ESA missions are written in bold letters.

Table 1: Actual satellite missions of high geodetic relevance

mission	science objectives	mission duration
CHAMP (G)	gravity/magnetic field/atmosphere	2000 – 2005
GRACE (USA/G)	gravity (stationary & temporal), atmosphere	2002 – 2007
GOCE (ESA)	gravity (stationary, high resolution)	2006 – 2008
TOPEX-POSEIDON (USA/F)	ocean altimetry	1992 – 2004
Jason-1 (USA/F)	ocean altimetry	2001 – 2006
ICESAT (USA)	ice altimetry	2003 – 2008
CRYOSAT (ESA)	ice altimetry	2004 – 2007
ERS-2 (ESA)	altimetry/climate/environiment	1995 – 2005
ENVISAT (ESA)	altimetry/climate/environment	2002 – 2007
TerraSAR-X (G)	SAR/INSAR/atmosphere	2005 – 2010
LAGEOS-1 & 2 (USA)	reference system, gravity	1975 - open
GPS (USA)	navigation/positioning/orbits/time/Earth rotation...	1978 - open
GALILEO(EU, ESA)	navigation/positioning...	2008 - open

High-lights of greatest immediate geodetic interest were the successful launch of CHAMP (CHallenging Minisatellite Payload) in July 2000, (REIGBER et al., 2003), the launch of the two twin satellites GRACE (Gravity Recovery and Climate Experiment) in March 2002, (PERKINS, 2003, Tapley 2002, or <http://www.csr.utexas.edu/grace/>), and the approval of the gravity gradiometric satellite mission GOCE (Gravity field and steady-state Ocean Circulation Explorer) by ESA, (ESA, 1999). With these three missions a new generation

of satellite gravity sensing systems becomes available and in succession all three fundamental approaches, high-low satellite-to-satellite tracking combined with micro-accelerometry (CHAMP), low-low satellite-to-satellite tracking combined with micro-accelerometry (GRACE) and gravity gradiometry (GOCE) are realized. Of particular interest is the fact that CHAMP and GRACE will aim at the measurement of temporal gravity variations. With these missions – in conjunction with the geometric/geo-kinematic satellite

missions such as GPS, ocean and ice altimetry, and InSAR – geodesy can address a very central theme of Earth system research: the determination of mass anomalies, mass transport, mass exchange and mass balance in and between the components of the Earth system.

Already the preliminary results from CHAMP and GRACE, available so far, exceed all previous models in terms of accuracy and consistency. Considerable research during the past four years went into the development of sensor and data simulation and analysis methods for these missions and into the establishment of data archiving structures.

References

- DICK, W., B. RICHTER (eds.) (2002) *IERS Annual Report 2001*, International Earth Rotation Service, Central Bureau, Frankfurt/Main, 123 pages.
- European Space Agency (1999) *Gravity Field and Steady-State Ocean Circulation*, ESA SP-1233(1) – The Four Candidate Explorer Core Missions, ESA Publication Division, Noordwijk, 215 pages. 261 pages.
- PERKINS, S. (2003) *Mapping with GRACE*, Science News online, 163, 1, page 6.
- REIGBER, CH., H. LÜHR, P. SCHWINTZER (eds.) (2003) *First CHAMP Mission Results for Gravity, Magnetic and Atmospheric Studies*, Springer, Berlin, 563 pages.
- RUMMEL, R., H. DREWES, W. BOSCH, H. HORNIK (eds.) (2000) *Towards an Integrated Global Geodetic Observing System (IGGOS)*, IAG Symposia, Volume 120, Springer, Berlin.
- TAPLEY, B.D. (2002) *The GRACE mission: Status and performance assessment*. American Geophysical Union fall meeting. Dec. 6-10. San Francisco. Abstract.

Satellite gravity field missions

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Introduction

The four years since the last IUGG General Assembly in Birmingham were characterized by remarkable decisions and events related to gravity field research by satellites. The European Gravity and Ocean Circulation Explorer mission GOCE was selected at the end of 1999 as first ESA's Earth Explorer Core Mission. In July 2000, the German geoscientific small satellite CHAMP (Challenging Mini-Satellite Payload for Geophysical Research and Application) has been brought into a nearly circular orbit at an altitude of approximately 500 km. In March 2001, the American-German mission GRACE (Gravity Recovery and Climate Experiment) has been launched. CHAMP, GRACE and GOCE have the potential to revolutionize the knowledge of the system Earth. Not only the static part of the gravity field can be determined with unprecedented accuracy, also the temporal variations of the gravity field will be detected at the longer wavelengths. The three mission concepts based on satellite gravity gradient measurements (SGG) as to be realized in case of GOCE, the high-low satellite-to-satellite tracking concept (high-low SST) realized in CHAMP and the low-low satellite-to-satellite tracking concept (low-low SST) realized in case of GRACE are complementary mission concepts. SST is superior in the lower harmonics below degree and order 50 to 100. Furthermore a mission like GRACE is optimal for studying the time-varying gravity field effects at moderate wavelengths. One prerequisite to detect temporal effects is a corresponding mission duration of several years as expected for GRACE. The static part of the gravity field up to approximately degree 50 can be determined by CHAMP with high accuracy, even up to degree 100 by GRACE. The first results from CHAMP and GRACE confirm these expectations. A gradiometric mission as GOCE is superior in the short wavelengths parts of the gravity field up to a spherical harmonic degree of approximately 250.

Status of gravity field missions and first results

The best way to get information about the status of the missions CHAMP and GRACE and about the progress of preparations of GOCE are the Internet sites of GFZ Potsdam and the University of Texas, Austin, as well as the homepages of the European Space Agency ESA. More specific details were presented in the reports of REIGBER et al. (1999b, 2000 and 2002). The determination of good orbits for the LEOs (Low Earth Orbiters) based upon GPS observations is an important prerequisite for the gravity field recovery.

Corresponding approaches for CHAMP and other satellites can be found in SVEHLA and ROTHACHER (2002, 2003a, 2003b, 2003c). Additionally, OBERNDORFER et al. (2002a) and OBERNDORFER and MÜLLER (2003) investigated how CHAMP star tracker and accelerometer data can be combined to check each other mutually. The status and future plans concerning the mission GRACE was presented by TAPLEY and REIGBER (2002). An overview of the various mission concepts, which led finally to the selection of CHAMP, GRACE and GOCE as the most promising concepts, was given in ILK (2000). BALMINO et al. (1999a) and RUMMEL et al. (2002) compared the typical characteristics of the three gravity field missions. RUMMEL (2002) discussed gravity gradiometry from EÖTVÖS to GOCE. BALMINO et al. (1999b) gave a comprehensive description of the GOCE mission, which was the foundation for the selection of GOCE as the first of ESA's Earth Explorer Core missions. SNEEUW and FLURY (2001) presented GOCE-Geodesy activities in Germany. The first high-quality global gravity field model from CHAMP GPS tracking data and accelerometry, Eigen-1S, was presented in REIGBER et al. (2002a). First experiences and perspectives of GRACE orbit and gravity field recovery at GFZ Potsdam were reported in REIGBER et al. (2002b).

Development of sensor analysis techniques, validation and calibration

In Munich, a simulation tool for the integrated sensor analysis has been developed to be able to simulate the interaction of the various sensors on board of CHAMP, GRACE and GOCE; see MÜLLER and OBERNDORFER (1999), OBERNDORFER et al. (1999, 2000, 2002a, 2002b), SMIT et al. (2000), SNEEUW et al. (2001), OBERNDORFER and MÜLLER (2002) and FROMMKNECHT et al. (2002). Energy relations for the motion of two satellites within the gravity field of the Earth as a tool for validation of gravity field computations and orbit determinations were treated by ILK (2000, 2002). Further aspects of possible calibration/validation procedures concerning the GOCE mission, e.g. by combination with terrestrial gravity data, were addressed in DENKER (2003) and MÜLLER et al. (2003). KLEES et al. (2000), RUMMEL et al. (2000), SMIT et al. (2000), SNEEUW et al. (2002) and MÜLLER (2001, 2003) discussed specific features relevant for GOCE processing, like reference frames, data filtering or error analyses. Possible synergies of GOCE with the CHAMP and GRACE missions were indicated in GRUBER (2001).

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Development of gravity field analysis techniques

The developments of gravity field analysis techniques are reported in the remaining parts of the present Section II (Advanced Space Technology) and in Section III (Determination of the Gravity Field) of this report. As far as mathematical and stochastic aspects are concerned, additional papers are discussed in Section IV (General Theory and Methodology). Here we will refer especially to those reports which are exclusively related to the satellite gravity field missions CHAMP, GRACE and GOCE. Satellite dynamics of the CHAMP and GRACE LEOs as revealed from space- and ground-based tracking was investigated by KÖNIG et al. (2002). SCHWINTZER and REIGBER (2002) reported on the contribution of GPS flight receivers to global gravity field recovery. The analysis of the Earth's gravitational field from semi-continuous ephemerides of a low Earth orbiting GPS-tracked satellite of type CHAMP was presented by AUSTEN et al. (2002), AUSTEN and REUBELT (2000), REUBELT (2000) and by REUBELT et al. (2002) as well as by SCHÄFER and GRAFAREND (2002). A sensitivity analysis of GPS-tracked satellite missions by Space Gravity Spectroscopy was reported in SCHÄFER (2002). The determination of regional parts of the gravity field of the Earth from satellite-to-satellite tracking and satellite gravity gradiometry was investigated by ILK (2002). The impact of terrestrial data on future satellite gravity field solutions was investigated by KUSCHE et al. (2000). ROLAND and DENKER (2003) discussed the combination of the CHAMP gravity field with terrestrial gravity data. A contribution to data combination in ill-posed downward continuation problems was presented by ILK et al. (2002). The important question of regularization in case of geopotential determination from satellite data by variance components was discussed in KOCH and KUSCHE (2002). The polar gap problem, a critical issue in processing GOCE measurements, was treated in KUSCHE and ILK (2000) and in RUDOLPH et al. (2000, 2002). ALBERTELLA et al. (1999) and ALBERTELLA and SNEEUW (2000) discussed also the polar gap problem, but in the context of the slepian problem. Effects of inhomogeneous data coverage on spectral analysis, important for the analysis of GOCE measurements, was investigated in PAIL and SCHUH (2000). The question of spatially restricted data distributions on the sphere and the method of orthonormalized functions was investigated in PAIL et al. (2001). Numerical solution strategies for global gravity field determination were further discussed in PLANK and SCHUH (2001), SCHUH et al. (2001), and SCHUH (1999, 2000), as far as filtering techniques are concerned in SCHUH (2001, 2002a) and in case of the presence of data gaps in SCHUH (2002b). The numerical treatment of the downward continuation problem in context with the analysis of GOCE measurements was investigated in SCHUH and KARGOLL (2002). SNEEUW (2000, 2001) developed a semi-analytical approach to gravity field analyses from satellite observations. GERLACH et al. (2003a, 2003b) and SNEEUW et al. (2003) applied the energy balance approach to CHAMP gravity field recovery – for the static and temporal parts.

Applications of satellite gravity field missions

The impact of the GOCE mission for ocean circulation studies was investigated by DOMBROWSKI et al. (1999) and SCHRÖTER et al. (2002). GRUBER and STEIGENBERGER (2003) discussed also a possible benefit for oceanography applying the gravity field missions. A short overview of GOCE applications can be found in SNEEUW et al. (2000) or in MÜLLER (2001). RUMMEL (2000a, 2000b) and VISSER et al. (2002) reported about various applications of GOCE in the geosciences, e.g. in solid-earth physics, oceanography or geodesy. REIGBER et al. (1999a) investigated the effect of temporal gravity field variations from different sources and their impact in the satellite data. FLECHTNER et al. (2002) reported on atmospheric and oceanic gravity de-aliasing for GRACE. PETERS et al. (2002) investigated the effect of atmospheric pressure variations in the satellite data.

References

- ALBERTELLA, A., SNEEUW, N.: *The Analysis of Gradiometric Data with Slepian Functions*, Phys. Chem. Earth (A), Vol. 25, Nr. 9-11, pp. 667-672, 2000
- ALBERTELLA, A., SANSÒ, F., SNEEUW, N.: *Band-limited functions on a bounded spherical domain: the Slepian problem on the sphere*, Journal of Geodesy, 73, pp. 436-447, 1999
- AUSTEN, G., GRAFAREND, E.W., REUBELT, T.: *Analysis of the Earth's gravitational field from semi-continuous ephemerides of a low Earth orbiting GPS-tracked satellite of type CHAMP, GRACE or GOCE*, in: J. Adam, K.P. Schwarz (eds.): *Vistas for Geodesy in the New Millennium*, 309-315, Springer, Berlin, Heidelberg, 2002
- AUSTEN, G., REUBELT, T.: *Räumliche Schwerefeldanalyse aus semi-kontinuierlichen Ephemeriden niedrigfliegender GPS-vermessener Satelliten vom Typ CHAMP, GRACE und GOCE (Spatial gravity field analysis using semi-continuous ephemerides of low-orbiting GPS-tracked satellites of type CHAMP, GRACE and GOCE)*, Diploma thesis, Geodetic Institute, University of Stuttgart, Germany, 2000
- BALMINO, G., PEROSANZ, F., RUMMEL, R., SNEEUW, N., SÜNKEL, H.: *CHAMP, GRACE and GOCE: Mission concepts and simulations*, Boll. Geof. Teor. Applic., 40, 3-4, pp. 309-319, 1999a
- BALMINO, G., RUMMEL, R., VISSER, P., WOODWORTH, P.L.: *Gravity Field and Steady-State Ocean Circulation Mission*, in: *The Four Candidate Earth Explorer Core Missions*, ESA, SP-1233 (1), 217 pages, 1999b
- DENKER, H.: *Computation of Gravity Gradients Over Europe for Validation/Calibration of GOCE Data*, in: *Proceedings of the 3rd Meeting of the International Gravity and Geoid Commission*, Thessaloniki, Greece, in print, 2003
- DOMBROWSKI, E., LEGRAND, P., LEPROVOST, C., LE TRAON, P.Y., LOSCH, M., PONCHAUT, F., SCHRÖTER, J., SLOYAN, B., SNEEUW, N.: *Impact of the GOCE mission for ocean circulation study*, Report European Space Agency, Contract ESTEC Nr 13175/98/NL/GD, 157 pages, 1999
- FLECHTNER, F., ZLOTNICKI, V., PEKKER, T.: *Atmospheric and oceanic gravity de-aliasing for GRACE*, EGS XXVII General Assembly, Nice, France, April 2002, abstract id EGS02-A-01557, 2002
- FROMMKNECHT, B., OBERNDORFER, H., FLECHTNER, F., SCHMIDT, R.: *Integrated Sensor Analysis of GRACE - Development and Validation*, EGS XXVII General Assembly, Nice,

- France, April 2002, submitted to *Advances in Geosciences*, 2002
- GERLACH, C., SNEEUW, N., VISSER, P., SVEHLA, D.: *CHAMP Gravity field recovery with the energy balance approach: first results*, in: *First CHAMP Mission results for Gravity, Magnetic and Atmospheric Studies*. C.Reigber, H.Lühr, P.Schwintzer (eds.), pp. 134-139, Springer Verlag, 2003a
- GERLACH, C., SNEEUW, N., VISSER, P., SVEHLA, D.: *CHAMP gravity field recovery using the energy balance approach*, EGS XXVII Assembly, Nice, France, *Advances in Geosciences*, accepted, 2003b
- GRUBER, TH.: *Identification of Processing and Product Synergies for Gravity Missions in View of the CHAMP and GRACE Science Data System Developments*, Proceedings of 1st International GOCE User Workshop, ESA Publication Division, Report WPP-188, 2001
- GRUBER, TH, STEIGENBERGER, P.: *Impact of New Gravity Field Missions for Sea Surface Topography Determination*, in: Proceedings of the 3rd Meeting of the International Gravity and Geoid Commission, Thessaloniki, in print, 2003
- ILK, K.H.: *Energiebetrachtungen für die Bewegung zweier Satelliten im Gravitationsfeld der Erde*, F. Krumm, V.S. Schwarze (eds.) "Festschrift für Erik W. Grafarend on the occasion of his 60th birthday", Schriftenreihe der Inst. D. Stud. Geodäsie u. Geoinformatik 1999.6-1, University Stuttgart, Stuttgart, 1999
- ILK, K.H.: *Envisaging a new area of gravity field research*, in: *Towards an Integrated Global Geodetic Observing System (IGGOS)*, (eds.) Rummel, R., Drewes, H., Bosch, W., Hornik, H., IAG Symposium 120, pp. 53-62, Springer, 2000
- ILK, K.H.: *Energy Relations for the Motion of two Satellites within the Gravity Field of the Earth*, in: M.G. Sideris (ed.): "Gravity, Geoid and Geodynamics 2000", IAG Symposia Vol. 123, pp. 129-135, Springer Verlag, 2001
- ILK, K.H.: *Energy Relations for Satellite-to-Satellite Motions*, "Festschrift für Erik W. Grafarend on the occasion of his 60th birthday", Springer, 2001
- ILK, K.H.: *Regional Determination of the Gravity Field*, presented at the First Internat. Champ Workshop, GFZ Potsdam, 2002
- ILK, K.H.: *Energy Relations for Satellite-to-Satellite Motions*, in: E.W. Grafarend, F.W. Krumm, V.S. Schwarze (eds.): *Geodesy - The Challenge of the 3rd Millenium*, Springer, Berlin, Heidelberg, New York, 2002
- ILK, K.H., KUSCHE, J., RUDOLPH, ST.: *A Contribution to Data Combination in Ill-posed Downward Continuation Problems*, *Journal of Geodynamics* 33, pp. 75-99, Pergamon, 2002
- KLEES, R., KOOP, R., VISSER, P., VAN DEN IJSSEL, J., RUMMEL, R.: *Data Analysis for the GOCE Mission*, in: *Geodesy Beyond 2000* (ed: K.P. Schwarz), IAG-Symposia, 121, pp. 68-74, Springer, Heidelberg, 2000
- KOCH, K.R., KUSCHE, J.: *Regularization of geopotential determination from satellite data by variance components*, *Journal of Geodesy*, 76, pp. 259-268, Springer Verlag, 2002
- KÖNIG, R., REIGBER, CH., NEUMAYER, K.H., SCHMIDT, R., ZHU, S.Y., FLECHTNER, F., MEIXNER, H.: *Satellite Dynamics of the CHAMP and GRACE Leos as revealed from space- and ground-based tracking*, paper presented at the Joint COSPAR/IAC Panel on Satellite Dynamics (PSD1-B2.1) at the 34th Scientific Assembly of the Committee on Space Research (COSPAR), Houston, TX, USA, Oct 16-17, 2002, submitted to *Advances in Geosciences*, 2002
- KUSCHE, J., ILK, K.H.: *The Polar Gap Problem*, in: H. Sünkel (ed.), *From Eötvös to Milligal, Final Report, ESA Study, ESA/ESTEC Contract No. 13392/98/NL/GD*, 2000
- KUSCHE, J., ILK, K.H., RUDOLPH, S.: *Impact of terrestrial data on future satellite gravity field solutions*, in: *Towards an Integrated Global Geodetic Observing System (IGGOS)*, Rummel, R., Drewes, H., Bosch, W., Hornik, H. (eds.), IAG symposium 120, pp. 189-192, Springer, 2000
- MÜLLER, J.: *Die Satellitengradiometrie GOCE - Theorie, technische Realisierung und wissenschaftliche Nutzung*, Veröffentlichung der Deutschen Geodätischen Kommission, Reihe C, Nr. 541, München, 2001
- MÜLLER, J.: *GOCE gradients in various reference frames and their accuracies*, in: Proceedings of session G1 The new gravity field missions (CHAMP, GRACE, GOCE): from measurements to geophysical interpretation of the EGS General Assembly, Nice, France, 2002, *Advances in Geosciences*, in print, 2003
- MÜLLER, J., JARECKI, F., WOLF, K.I.: *External calibration and validation of GOCE gradients*, in: Proceedings of the 3rd Meeting of the International Gravity and Geoid Commission, Thessaloniki, Greece, in print, 2003
- MÜLLER, J., OBERNDORFER, H.: *Validation of GOCE Simulation*. Schriftenreihe des Instituts für Astronomische und Physikalische Geodäsie und der Forschungseinrichtung Satellitengeodäsie, IAPG/FESG No. 1, München, 1999
- MÜLLER, J., OBERNDORFER, H.: *Simulation of the Gradiometer Mission GOCE*, *Artificial Satellites*, Vol. 34, No. 1, pp. 41-55, 1999
- MÜLLER, J., OBERNDORFER, H., GERLACH, C., SNEEUW, N.: *Recent Simulation of the Gravity field mission GOCE*, Proceedings CD of the IAG General Assembly 2001, published on CD only, Budapest, 2002
- OBERNDORFER, H., MÜLLER, J., DOROBANTU, R., GERLACH, C., RUMMEL, R., SNEEUW, N., KOOP, R., VISSER, P., HOYNG, P., SELIG, A., SMIT, M.: *Simulation of the GOCE Gravity Field Mission*, in: *Towards an Integrated Global Geodetic Observing System (IGGOS)*, Proceedings of the IAG Section II Symposium, held in Munich, Germany, Oct. 5-9, 1998, IAG Symposia, Vol. 120, pp. 201-204, Springer Verlag, 2000
- OBERNDORFER, H., DOROBANTU, R., GERLACH, C., MÜLLER, J., RUMMEL, R., SNEEUW, N., KOOP, R., VISSER, P., HOYNG, P., SELIG, A., SMIT, M.: *GOCE Sensor Combination and Error Analysis*, in: Proceedings of the 2nd Joint Meeting of the International Gravity Commission (IGC) and the International Geoid Commission (IGeC), held in Trieste, Italy, Sept. 7 - 12, 1998, *Bolletino di Geofisica teorica ed applicata*, Vol. 40, No. 3-4, pp. 303-307, 1999
- OBERNDORFER, H., MÜLLER, J.: *GOCE Closed-loop Simulation*, in: *Earth's Gravity and Magnetic Fields from Space*, *Journal of Geodynamics*, Vol. 33, No. 1-2, pp. 53-63, 2002
- OBERNDORFER, H., MÜLLER, J.: *CHAMP Accelerometer and Star Sensor Data Combination*, in: *First CHAMP Mission results for Gravity, Magnetic and Atmospheric Studies*. C.Reigber, H.Lühr, P.Schwintzer (eds.), pp. 26-31, Springer Verlag, 2003.
- OBERNDORFER, H., MÜLLER, J., GRUNWALDT, L.: *On the potential of a combined use of CHAMP Star Tracking and Accelerometry*, in: IAG Symposium 125: *Vistas for Geodesy in the New Millenium*, J.Adam and K.-P.Schwarz (eds.), pp. 162-166, Springer Verlag, 2002a

- OBERNDORFER, H., MÜLLER, J., RUMMEL, R., SNEEUW, N.: *A Simulation Tool of the new Gravity Field Satellite Missions*, Adv. Space Res., Vol. 30, No. 2, pp. 227-232, 2002b
- PAIL, R., PLANK, G., SCHUH, W.-D.: *Spatially restricted data distributions on the sphere: the method of orthonormalized functions and applications*, J. Geodesy, Vol.75, pp. 44-56, Journal of Geodesy, 2001
- PAIL, R., SCHUH, W.-D.: *Effects of inhomogeneous data coverage on spectral analysis*, R. Rummel et al. (Hrsg.): Towards an Integrated Global Geodetic Observing System (IGGOS), IAG Symposia. Series 120, pp. 209-213, Springer, Berlin - Heidelberg, 2000
- PETERS, T., MÜLLER, J., SNEEUW, N.: *Temporal Variations in the Gravity field*, in: Vorträge beim 4. DFG-Rundgespräch im Rahmen des Forschungsvorhabens 'Rotation der Erde' zum Thema 'Wechselwirkungen im System Erde', Höllenstein/Wetzell, 08./09. März 2001, H.Schuh, M.Soffel, H.Hornik (eds.), Deutsche Geodätische Kommission, Reihe A, No. 118, pp. 133-140, 2002
- PLANK, G., SCHUH, W.-D.: *Numerical solution strategies for global gravity field determination*, Proceedings of the 8th International Meeting on „Alpine Gravimetry“, Leoben 2000. Österreichische Beiträge zu Meteorologie und Geophysik, Heft 26, 2001
- REIGBER, CH., BALMINO, G., SCHWINTZER, P., BIANCALE, R., BODE, A., LEMOINE, J.-M., KÖNIG, R., LOYER, S., NEUMAYER, H., MARTY, J.-C., BARTHELMES, F., PEROSANZ, F., ZHU, S.Y.: *A High-Quality Global Gravity Field Model from CHAMP GPS Tracking Data and Accelerometry (EIGEN-1S)*, Geophysical Research Letters 29 (14), 10.1029/2002GL01506, 2002a
- REIGBER, CH., BARTHELMES, F., GREINER-MAI, H., GRUBER, TH., JOCHMANN, H., WÜNSCH, J.: *Temporal Gravity Field Variations from oceanic, atmospheric and inner core Mass Redistributions and their Sensitivity to new Gravity Missions CHAMP and GRACE*, Bolletino di Geofisica Teorica ed Applicata, Vol. 40, 3-4, 329-340, 1999a
- REIGBER, CH., FLECHTNER, F., KOENIG, R., MEYER, U., NEUMAYER, K.H., SCHMIDT, R., SCHWINTZER, P., ZHU, S.Y.: *GRACE Orbit and Gravity Field Recovery at GFZ Potsdam, First Experiences and Perspectives*, EOS Trans. AGU, 83(47), Fall Meet. Suppl., Abstract G12B-03, 2002b
- REIGBER, CH., LÜHR, H., SCHWINTZER, P.: *Status of CHAMP Mission*, in: Rummel, Drewes, Bosch, Hornik (Eds.): Towards an Integrated Global Geodetic Observing System (IGGOS). International Association of Geodesy Symposia, Vol 120, 63-65, 2000
- REIGBER, CH., LÜHR, H., SCHWINTZER, P.: *CHAMP Mission Status*, Advances Space Research 30 (2), 129-134, 2002
- REIGBER, CH., SCHWINTZER, P., LÜHR, H.: *The CHAMP Geopotential Mission*. Bolletino di Geofisica teoretica ed applicata 40, special issue, Proceedings of 2nd Joint IGC and IGeC Meeting, Trieste, Sept. 1998, 285-289, 1999b
- REUBELT, T.: *Analyse der Satellitenbewegungsgleichung mit Hilfe kartesischer Bahnkoordinaten am Beispiel des CHAMP-Satelliten (Analysis of the equation of motion of a satellite using cartesian coordinates: The CHAMP satellite)*, study report, Geodetic Institute, University of Stuttgart, Germany, 2000
- REUBELT, T., AUSTIN, G., GRAFAREND, EW.: *Harmonic analysis of the earth's gravitational field by means of semi-continuous ephemeris of a Low earth orbiting (LEO) GPS tracked satellite*, Journal of Geodesy, Springer, 2002
- ROLAND, M., DENKER, H.: *Evaluation of Terrestrial Gravity Data by New Global Gravity Field Models*, 3rd Meeting of the International Gravity and Geoid Commission, 26.-30. Aug. 2002, Thessaloniki, Greece, in print, 2003
- RUDOLPH, S., KUSCHE, J., ILK, K.H.: *Investigations on the polar gap problem in ESA's gravity field and steady-state ocean circulation explorer mission*, in: M.G. Sideris (ed.): "Gravity, Geoid and Geodynamics 2000", IAG Symposia Vol. 123, Springer Verlag, 2000
- RUDOLPH, S., KUSCHE, J., ILK, K.H.: *Investigations on the polar gap problem in ESA's gravity field and steady-state ocean circulation explorer mission (GOCE)*, Journal of Geodynamics 33, pp. 65-74, Pergamon, 2002
- RUMMEL, R.: *Bright Prospects for a Significant Improvement of the Earth's Gravity Field Knowledge*, Marine Geodesy, 23, 3, pp. 219-220, 2000a
- RUMMEL, R.: *Fortschritte der Satellitengeodäsie*, NRWakW, Vorträge: Natur- Ingenieur- und Wirtschaftswissenschaften, No. 453, pp. 7-15, Westdeutscher Verlag, Wiesbaden, 2000b
- RUMMEL, R.: *Gravity Gradiometry: From Loránd Eötvös to modern space age*, Acta Geod. Hung., Vol. 37 (4), pp. 435-444, 2002
- RUMMEL, R., BALMINO G., JOHANNESSEN J., VISSER P., WOODWORTH P.: *Dedicated Gravity Field Missions - Principles and Aims*, Journal of Geodynamics, 33, 3-20, 2002
- RUMMEL, R., MÜLLER, J., OBERNDORFER, H., SNEEUW, N.: *Satellite Gravity Gradiometry with GOCE*, in: Towards an Integrated Global Geodetic Observing System (IGGOS), Proceedings of the IAG Section II Symposium, held in Munich, Germany, Oct. 5-9, 1998, IAG Symposia, Vol. 120, pp. 66-72, Springer Verlag, 2000
- SCHÄFER, C.: *Space Gravity Spectroscopy - The sensitivity analysis of GPS-tracked satellite missions (case study CHAMP)*, Deutsche Geodätische Kommission, Bayerische Akademie der Wissenschaften, Report C 534, 2001
- SCHÄFER, C., GRAFAREND, E.W.: *On the determination of gravitational information from GPS-tracked satellite missions*, Artificial Satellites, J. Planetary Geodesy 37, 31-49, 2002
- SCHRÖTER, J., LOSCH, M., SLOYAN, B.: *Impact of the Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) mission on ocean circulation estimates, volume and heat transports across hydrographic sections of unequally spaced stations*, Journal of Geophysical Research, 107 (C2), 4-1 - 4-20, 2002
- SCHUH, W.-D.: *Scientific data processing algorithms*, ESA-Project "From Eötvös to mGal", WP 3.1, Final-Report, 2000
- SCHUH, W.-D.: *Improved modeling of SGG-data sets by advanced filter strategies*, ESA-Project "From Eötvös to mGal", WP 2, Final-Report, 2002a
- SCHUH, W.-D.: *The processing of band-limited measurements; filtering techniques in the least squares context and in the presence of data gaps*, Proceedings of the Workshop "Earth Gravity Field from Space - from Sensors to Earth Sciences", Bern (March 11-15, 2002), Space Science Reviews (accepted paper), 2002b
- SCHUH, W.-D., KARGOLL, B.: *The numerical treatment of the downward continuation problem for the gravity potential*, Vth Hotine-Marussi-Symposium, Matera, Italy (June 17-21, 2002), to be published, 2002
- SCHUH, W.-D., PAIL, R., PLANK, G.: *Assessment of different numerical solution strategies for gravity field recovery*,

- Proceedings of the "International GOCE User Workshop", ESTEC, Noordwijk, The Netherlands (April 23-24, 2001), pp. 87-95, 2001
- SCHWINTZER, P., REIGBER, CH.: *The Contribution of GPS Flight Receivers to Global Gravity Field Recovery*, Journal of Global Positioning Systems 1(1), 61-63, 2002
- SMIT, M., KOOP, R., VISSER, P., VAN DEN IJSSEL, J., SNEEUW, N., MÜLLER, J., OBERNDORFER, H.: *GOCE End-to-End Performance Analysis*, Final Report, ESTEC Contract No.12735/98/NL/GD, 2000
- SNEEUW, N.: *A Semi-Analytical Approach to Gravity Field Analysis from Satellite Observations*, Deutsche Geodätische Kommission, Reihe C, Nr. 527, 2000, or <http://tumbi.biblio.tu-Muenchen.de/publ/diss/bv/2000/sneeuw.html>
- SNEEUW, N.: *Satellite geodesy on the torus – Block-diagonality from a semi-analytical approach*, in: Gravity, Geoid and Geodynamics 200, IAG Symposium 123, pp. 137-142, Springer Verlag, 2001
- SNEEUW, N., DOROBANTU, R., GERLACH, C., MÜLLER, J., OBERNDORFER, H., RUMMEL, R., KOOP, R., VISSER, P., HOYNG, P., SELIG, A., SMIT, M.: *Simulation of the GOCE Gravity Field Mission*, in: Proceedings of the Hotine-Marussi Symposium, held in Trento, Italy, Sept. 14-17, 1998, IAG Symposia 122, pp. 14-20, Springer, 2001
- SNEEUW, N., FLURY, J.: *GOCE – Geodesy activities in Germany*, in: Proceedings of the 1. International GOCE User Workshop, ESA Publication Division, Report WPP-188, ESA/ESTEC Noordwijk, 2001
- SNEEUW, N., GERLACH, C., MÜLLER, J., OBERNDORFER, H., RUMMEL, R.: *Fundamentals and Applications of the Gravity Field Mission GOCE*, in: Towards an Integrated Global Geodetic Observing System (IGGOS), Proceedings of the IAG Section II Symposium, held in Munich, Germany, Oct. 5-9, 1998, IAG Symposia, Vol. 120, pp. 205-208, Springer Verlag, 2000
- SNEEUW, N., GERLACH, C., SVEHLA, D., GRUBER, C.: *A first attempt at time-variable gravity recovery from CHAMP using the energy balance approach*, The 3rd Meeting of the International Geoid and Gravity Commission. GG2002 Thessaloniki, Greece, in print, 2003
- SNEEUW, N., VAN DEN IJSSEL, J., KOOP, R., VISSER, P., GERLACH, C.: *Validation of fast pre-mission error analysis of the GOCE gradiometry mission by a full gravity field recovery simulation*, Journal of Geodynamics, Vol 33, No. 1-2, 2002
- SVEHLA, D., ROTHACHER, M.: *Kinematic Orbit Determination of LEOs Based on Zero- or Double-Difference Algorithms Using Simulated and Real SST Data*, IAG 2001 Scientific Assembly, Budapest, Vistas for Geodesy in the New Millennium, Adam J., Schwarz K.P. (Eds), Springer IAG, Vol. 125, pp. 322-328, 2002
- SVEHLA, D., ROTHACHER, M.: *CHAMP double-difference kinematic POD with ambiguity resolution*, in: First CHAMP Mission results for Gravity, Magnetic and Atmospheric Studies. C.Reigber, H.Lühr, P.Schwintzer (eds.), pp. 70-77, Springer Verlag, 2003a
- SVEHLA, D., ROTHACHER, M.: *Kinematic and Reduced-Dynamic Precise Orbit Determination of Low Earth Orbiters*, EGS XXVII Assembly, Nice, France, Advances in Geosciences, accepted, 2003b
- SVEHLA, D., ROTHACHER M.: *Comparison of kinematic and reduced-dynamic orbit determination strategies for CHAMP and JASON*. The World Space Congress 2002, 34th COSPAR Scientific Assembly, Houston, Texas, US, Advances in Space Research, in print, 2003c
- TAPLEY, B.D., REIGBER, CH.: *The GRACE mission: status and future plans*, EGS XXVII General Assembly, Nice, France, April 2002, abstract id EGS02-A-04819, 2002
- VISSER, P.N.A.M., RUMMEL, R., BALMINO, G., SÜNKEL, H., JOHANNESSEN, J., AGUIRRE, M., WOODWORTH, P.L., LE PROVOST, C., TSCHERNING, C.C. & SABADINI, R.: *The European Earth Explorer Mission GOCE: Impact for the Geosciences, Ice Sheets, Sea level and the Dynamic Earth*, Geodynamics Series 29, American Geophysical Union, 95-107, 2002

GNSS, SLR, VLBI and SAR

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Several universities, government agencies, research centres and specialized companies more or less active in the aerospace sector have been actively involved in observation and data processing systems for GPS and GLONASS, the development of Europe's satellite navigation system GALILEO and in Satellite Laser Ranging as well as VLBI and SAR. This section summarizes the main activities in this field during the reporting period.

GNSS (GPS, GLONASS, GALILEO)

New work on the direct solution of the GPS pseudo-ranging equations using a multi-polynomial resultant and a Groebner basis algorithm in context of non-linear adjustment (AWANGE & GRAFAREND, 2002) has been presented. Investigations concerning the reliability and the external accuracy of GPS Real-Time Measurements (ILLNER, 2002) and to identify the correlation length of carrier-phase measurements (HOWIND et al, 2000) have been performed. Four space-borne GPS receiver missions are/were flown with significant German participation: On-board of the the German CHAMP (CHALLENGING Microsatellite payload) mission (GFZ Potsdam PI, launched in July 2000) the Black Jack GPS flight receiver TSRS-2, provided by NASA and manufactured at Jet Propulsion Laboratories (JPL), is in operation, mainly for radio occultation experiments (WICKERT et al, 2001). It is also used for CHAMP precise orbit determination in differential GPS mode in combination with a ground-based GPS tracking network (REIGBER et al, 2000; GALAS et al, 2001). On the joint German/American GRACE (BALMINO et al, 1999) twin-satellite mission (GFZ Potsdam Co-PI, launched in March 2002) a GPS TurboRogue space receiver assembly provided by JPL serves for precise orbit determination (POD) with cm-accuracy, real-time coarse positioning (< 50 m), time tagging and atmospheric profiling. The German Space Operation Center of DLR is flying since Oct. 2001 a GPS receiver (Rockwell Collins, GEM III) on the BIRD small satellite (GILL & MONTENBRUCK, 2001). The receiver is used as a sensor for autonomous space navigation. Results of the successful GPS-Experiment on the highly elliptical orbit mission Equator-S (64.000 km away from earth, above GPS constellation, most distant signal to GPS PRN 30 received over 61.000 km) have been presented (BALBACH et al, 1999). By the same authors (BALBACH & EISSFELLER, 1999) the use of so-called GPS Block IIF space pointing antennas for orbit determination of geostationary satellites has been

analysed. Basic research on the use of GPS pseudolites on the ground and the identification of specific problem areas went on (BIBERGER et al, 2001).

Although the GLONASS constellation was significantly degraded (due to funding problems of the Russian federation) during the reporting period (sometimes less than 7 operational spacecraft) the remaining GLONASS satellites still were monitored by the DLR, Institute of Communications and Navigation (IKN), Neustrelitz. In the GLOMO project (REIMER, 2000) three dual frequency GLONASS receivers have been installed (Neustrelitz, Oberpfaffenhofen, Ispra) and were operated for data acquisition. An interface was built-up with the Russian GLONASS Master Control Station (MCC) near Moscow. Data on the status of GLONASS was provided by the BKG via the GIBS information and observation system. Besides this no major research activities on GLONASS can be reported.

In March 2002 the European ministers of transport made the fundamental decision to launch the development phase for Europe's independent satellite navigation system GALILEO. Several overview papers were presented (WEBER et al, 2001; EISSFELLER, 2002) with the purpose to provide information about the basic features of the planned GALILEO system. In the geodetic community mainly the University of the Armed Forces was involved in the definition and development process: Some contributions address the problem of how to define a high-performance signal structure for GALILEO (EISSFELLER et al, 2000; HEIN et al, 2002) and how to assess inter-operability as well as compatibility issues with a modernized GPS. Others address the integrity issue (HEIN et al, 1999; ZINK et al, 2000) and the combined use of GALILEO and GPS measurements for future high-precision RTK systems (TIBERIUS et al, 2002). Also the advantages and disadvantages of the use of C-Band signals for GALILEO have been investigated (IRSIGLER et al, 2002). Similar investigations were performed by the DLR- IKN group (SCHWEIKERT et al, 2000).

Orbit Monitoring by SLR, PRARE, DORIS

Laser Ranging to artificial Satellites in Germany was carried out at the two stations: In Potsdam by the GeoForschungs-Zentrum (GFZ) and in Wettzell at the Fundamentalstation Wettzell which is operated by the Bundesamt für Kartographie und Geodäsie (BKG) and the Forschungseinrichtung

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Satellitengeodäsie (FESG) of the Technical University of Munich on behalf of the Forschungsgruppe Satellitengeodäsie (FGS). Both are involved in the EUROLAS consortium, whereas GFZ is additionally a member of the International Laser Ranging Service (ILRS).

Some modifications have been carried out at the Wettzell Laser Ranging System (WLRS) in order to improve the calibrations and to extend the tracking range which was designed for satellites orbiting the Earth between 800 km and 40.000 km altitude towards lower orbiting satellites (SCHLÜTER et al, 2002). The Modular Transportable Laser Ranging System (MLRS 1) is not any more in operation. BKG developed the Transportable Integrated Geodetic Observatory (TIGO) which requires manpower of the complete available staff (SCHLÜTER et al, 2002). All space techniques such as SLR, VLBI, GPS, PRARE are employed in TIGO. In addition to the space techniques also some in situ observables can be obtained, such as time and frequency, gravity, seismic, and meteorology observations. Tests of TIGO were conducted up to the year 2001 in collocation with the permanent installed space techniques at the observatory Wettzell in order to control the function and to improve TIGO. The system was shipped at the end of 2001 for the first field campaign to Concepcion/Chile. In collaboration with the local Universities in Concepcion/Chile namely the Universidad de Concepcion, Universidad Catolica de la Santisima Concepcion, Universidad del Bio Bio and the Instituto Geografico Militar, which joint to a consortium, TIGO was set up in the first quarter of 2002 and starts its routine operation in April 2003. TIGO provides data for all the space techniques and serves for the IAG services IGS, ILRS and IVS.

GFZ was operating the system, called POTSDAM-2, which is a precise 2 cm mode-locked Nd-YAG system, continuously contributing to the International Laser Ranging Service (ILRS). With this system a lot of LEO up-to MEO orbiting satellites have been tracked, e.g. LAGEOS-1&2, TOPEX, GPS, GLONASS, GFZ-1, ERS1 & 2, CHAMP, etc. Since 2000 a new system (a diode-laser pumped Nd-YAG oscillator with two mode-lockers), POTSDAM-3, is hosted in a tower attached to one of the GFZ buildings (NEUBERT et al, 2000). It is based on two separate telescopes for transmitting the laser pulse and receiving the return respectively. First LAGEOS ranging using the new system has been conducted at August 4, 2001 and continued in October-December 2001. From the first LAGEOS passes, preliminary station coordinates have been obtained.

During the reporting period the Precise Range and Range Rate Equipment (PRARE) system was in operation and is tracking the ERS-2 satellite on a routine basis (FALCK, 1999). Although some stations were abandoned, the state of the PRARE ground segment still shows potentially 24 stations, which are flagged active or unavailable on a daily basis.

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

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). 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 newly formed 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 Geodetic Institute of the University of Bonn (GIUB). The Deutsches Geodätisches Forschungsinstitut (DGFI) as well as BKG and GIUB 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. Germany is represented in the IVS Directing Board by three members, James Campbell (IAG Ex officio member), Wolfgang Schlüter (Chairman) and Axel Nothnagel (IVS Analysis Coordinator). The IVS Analysis Coordinator's office is hosted by the Geodetic Institute of the University of Bonn. 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.

In addition to the VLBI activities in the global framework, a program of on the average six observing sessions per year among the 10 European radio telescopes equipped for geodetic VLBI is being carried out under the coordination of the Geodetic Institute of the University of Bonn. A comprehensive report on the results of the EU-supported Project has been published recently (CAMPBELL, HAAS, NOTHNAGEL 2002).

On the technical side, a new MkIV correlator funded jointly by BKG and MPIfR has been installed at the Max-Planck-Institute for Radio Astronomy (MPIfR) in Bonn and has started operation in May 2000. Presently, the tape based data acquisition system is being replaced by a disk based system (MkV), which allows highly reliable data transfer between the stations and the correlator. This step will also ease the transition to a fully automated processing scheme. A comparison between the old MkIII and the new MkIV correlation results has been performed using a set of VLBI experiments correlated on both correlators (MÜSKENS et al. 2000, NOTHNAGEL et al. 2002).

BKG and FESG 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)

In collocation to the VLBI facilities a large Ringlaser „G“ was developed and realized as a local sensor for the observation of Earth rotation, in particular for the determination of high frequency variations of the UT1-UTC parameter. „G“ is expected to provide observations of the variations of Earth rotation with subdaily resolution. Because the realization of „G“ is completely unique world-wide, this project is mentioned here among the VLBI activities. VLBI is one of the major contributing techniques for the observation of Earth rotation and VLBI results are essential for the comparison and evaluation of the results obtained with „G“ (SCHREIBER et al. 2000, SCHREIBER et al. 2001) .

Combination of Space Geodetic Networks

Under the headline of "Combination of Space Geodetic Networks" two main research areas have to be reported: observing platforms and data analysis. The combination of different space geodetic techniques is only possible on the basis of a number of geodetic fundamental stations dedicated to more than at least two space geodetic observing platforms. Two of these fundamental stations are operated by German agencies: The Geodetic Fundamental Station Wettzell has been operational for almost 20 years now comprising VLBI, SLR, LLR, GPS, GLONASS, and PRARE equipment. Very recently, in January 2003, the Transportable Integrated Geodetic Observatory (TIGO) of BKG was declared operational at Concepcion, Chile (HASE et al. 1999; HASE et al. 2001). Within TIGO transportable VLBI and SLR telescopes as well as GPS receivers, a super-conducting gravimeter, a broad spectrum seismometer and meteorological sensors are being operated. The concept of fundamental stations is closely linked to the necessity of highly accurate inter-technique vectors at these sites. At Wettzell measurements have been carried out in regular intervals with high accuracy to satisfy this need (SCHLÜTER et al. 1999a). At Concepcion these measurements are currently being prepared.

It has been recognized that a combination of results from different space techniques has many benefits for the final products such as the International Terrestrial Reference Frame (ITRF) and the Earth orientation parameters (EOP). Firstly, the systematic differences of the individual techniques can be studied against a combined mean result from all available techniques. Secondly, the reliability of the products can be increased if the results are derived with a high degree of redundancy. This is especially important for global monitoring of continuously varying parameters.

In Germany, the groups and institutions concerned with observation and analysis of space geodetic networks have formed a Government-supported research consortium within the national contribution to IERS, i.e. the IERS Geotechnology Project. In this frame, BKG (IERS Central Bureau),

University of Munich (FESG/IERS Analysis Coordinator), DGFII (IERS Combination Research Center), University of Bonn (IERS Combination Research Center and VLBI Analysis Coordinator (IVS)) and GFZ (IERS Combination Research Center) are cooperating to develop a more rigorous and largely automated approach to the combination problem (ROTHACHER, 2000).

For aspects on Earth rotation and further references see Section V.

SAR and INSAR

Synthetic Aperture Radar (SAR) systems record both amplitude and phase of the backscattered echoes, typically in L-band, C-Band, X-band. If two SAR images from slightly different viewing angles are considered (interferometric pair) their phase difference (interferometric fringes) can be fully exploited to generate precise Digital Elevation Maps (DEMs) to monitor terrain changes and to improve the range resolution (INSAR).

The highlight in the reporting period was the flight of the Shuttle Radar Topography Mission (SRTM) payload (AIGNER & HELLWIG, 2000) onboard the Space Shuttle Endeavour (February 11-22, 2000). SRTM was a joint mission by NASA, NIMA, DLR and ASI. On the mission a C-band and a X-band system were flown in parallel, making use of transmit/receive antennae in the cargo bay and receive only antennae located at the end of a 60 m boom. During its ten days of operation 12 terabytes of raw SAR data have been acquired which are currently processed by different institutions. In Germany digital elevation models are generated and distributed by DFD (German Remote Sensing Data Center) of the DLR making use of the X-SAR data. Several university institutes (REICH & THIEL, 2002; KOCH & HEIPKE, 2001) were involved in the quality assessment and validation of the derived DEMs. Work on polarimetric SAR signatures, airborne differential INSAR and SAR tomography was performed by TU Berlin and DLR (REIGBER, 2002; REIGBER & SCHEIBER, 2002). Applications research was done on SAR monitoring of landuse change (CSAPLOVIC, 2000), landslide monitoring in the Three Georges Area using D-InSAR (XIA et al, 2002) and SAR-interferometry for monitoring co- and inter-seismic deformation (XIA et al, 1999). Fusion of optical imagery and SAR/INSAR data for object extraction, especially road extraction, is discussed in Hellwich, et al 2000.

References

- AIGNER E., HELLWICH O.: *Shuttle Radar Topography Mission – Erfolgreiche Mission zum Planeten Erde*. In: Mitteilungen der Technischen Universität München für Studierende, Mitarbeiter, Freunde: TUM Mitteilung 4-99/00 (2000), S. 25-26.
- AUGATH W, BROSSMANN M, SCHLÜTER W, SUDAU A, WINTER R.: *NNSAT: Precise Height Supervision of Tide Gauges with GPS*, Wegener Meeting Cadiz, Sept. 2000
- AWANGE J. L., GRAFAREND E. W.: *Algebraic solution of GPS pseudo ranging equations, GPS solutions 5, 20-32, 2002*

- AWANGE J. L., GRAFARENDE E. W.: *Nonlinear Adjustment of GPS Observations of Type Pseudo-Ranges*, GPS Solutions 5, 80-93, 2002
- BALBACH O., EISSFELLER B.: *Analyses of the Equator-S GPS Mission Data at Altitudes above the GPS-Constellation*. 4th ESA International Conference on Spacecraft Guidance, Navigation and Control Systems, ESTEC, Noordwijk, The Netherlands, Oct. 18-21 1999
- BALBACH O., EISSFELLER B., HEIN G. W.: *GPS Navigation of Geostationary Satellites Using GPS Block IIF Space Pointing Antennas*. ION GPS '99, 12th Int. Technical Meeting, Nashville, Tennessee, USA, Sept. 14-17, 1999
- BALMINO G., PEROSANZ F., RUMMEL R., SNEEUW N., SÜNKEL H.: *CHAMP, GRACE and GOCE: Mission concepts and simulations*, Boll. Geof. Teor. Aplic., 40,3-4,S. 309-319, 1999.
- BAUERNFEIND E., KILGER R., KRONSCHNABL G., SCHATZ R., SCHWARZ W., ZEITLHÖFLER R., ZERNECKE R., BIELMEIER E.: *Station Report of the 20 m Radiotelescope at Wettzell*, Annual Report 2001, IVS Coordinating Center, Febr. 2002
- BEHREND D., HAAS R., PINO D., GRADINARSKY L. P., KEIHM S. J., SCHWARZ W., CUCURULL L., RIUS A.: *MM5 derived ZWDs compared to observational results from VLBI, GPS and WVR*, Physics and Chemistry of the Earth, June 14, 2001
- BEUTLER G., DREWES H., REIGBER CH., RUMMEL R.: *Sace Techniques and their Coordination within IAG at Present and in Future*. In: Towards an Integrated Global Geodetic Observing System (IGGOS) (eds: R. Rummel, H. Drewes, W. Bosch, H. Hornik), IAG-Symposia, 120, S. 22-34, Springer, Heidelberg, 2000.
- BEYERLE G., HOCKE K., WICKERT J., SCHMIDT T., MARQUARDT C., REIGBER CH.: *GPS radio occultations with CHAMP: A radio holographic analysis of GPS signal propagation in the troposphere and surface reflections*, J. Geophys. Res., 10.1029/2001JD001402, 2002.
- BIBERGER R., HEIN G. E., EISSFELLER B., OEHLER V., SCHUELER T.: *Pseudolite Signal Creeping on Conducting Surfaces*, Proc. ION GPS-01, Salt Lake City, Utah, Sept. 11-14, 2001.
- CAMPBELL J.: *From Quasars to Benchmarks: VLBI links Heaven and Earth*. In: IVS 2000 General Meeting Proceedings, N.R. Vandenberg and K.D. Baver (eds.), NASA/CP-2000-209893, p. 20-34, 2000.
- CAMPBELL J.: *Very Long Baseline Interferometry – a high precision tool for geodesy and astrometry*. In: Comptes Rendus de l'Académie des Sciences Paris, tome 1, Série IV, p.1-12, 2000
- CAMPBELL J., NOTHNAGEL A.: *European VLBI for crustal dynamics*. Journal of Geodynamics, Vol. 30, p. 321-326, 2000
- CAMPBELL J.: *The significance of the European VLBI network for the concept of EUREF*. Symposium of the IAG Sub-commission for Europe (EUREF), held at Tromsø, 22-24 June 2000, Veröff. Bayer. Komm. Für die Internationale Erdmessung, Heft Nr. 61, EUREF-Publication No. 9, p. 187-192, München 2000
- CAMPBELL J., RICHTER B.: *Towards a stable European vertical velocity reference system using VLBI, GPS and absolute gravity measurements*. Proceedings of the 15th Working Meeting on European VLBI for Geodesy and Astrometry, held in Barcelona, Spain, Sept. 7-8, 2001, D. Behrend, A. Rius, Eds., IEEC-CSIC Barcelona, p. 65-74, 2001
- CAMPBELL J., HAAS R., NOTHNAGEL A. (EDS): *Measurement of Vertical Crustal Motion in Europe by VLBI*, TMR-Network Publication, Cat. No. KI-NA-20-084-ENC, ISBN 92-894-0763-8, European Commission, 2002
- CAMPBELL J., NOTHNAGEL A., VENNEBUSCH M.: *Measuring Crustal Deformation in Europe by High Precision Geodetic VLBI*. Proceedings of the 6th European VLBI Network Symposium, Bonn, 25-28 June 2002, ed. by E. Ros, R.W. Porcas, A.P. Lobanow and J. A. Zensus, Max-Planck-Institut für Radioastronomie, Bonn, p. 5-8, 2002
- CLOUDE S. R., PAPATHANASSIOU K. P., REIGBER A., BOERNER W. M.: *Multi-Frequency Polarimetric SAR Interferometry for Vegetation Structure Extraction*, Proceedings of IGARSS'2000, Honolulu, pp. 129-131, 2000.
- CLOUDE S. R., PAPATHANASSIOU K. P., REIGBER A.: *Polarimetric SAR Interferometry at P-Band for Vegetation Structure Extraction*, Proceedings of EUSAR'2000, Munich, pp. 249-252, 2000.
- CSAPLOVIC S. E.: *SAR-based monitoring of flood-induced land-cover and landuse change in the region of the inland delta of the river Niger (Mali)*. Proc ERS-Envisat Symp Gothenburg, Sweden, CD-ROM, 2000.
- EISSFELLER B.: *The European Satellite Navigation System GALILEO*. CGST Bulletin, Section II – Advanced Space Technology, Progress Report 2001, Deutsches Geodätisches Forschungsinstitut, München, pp. 51-59.
- EISSFELLER B., TIBERIUS C., PANYT., BIBERGER R., SCHUELER T., HEINRICH G.: *Real-Time Kinematic in the Light of GPS Modernization and Galileo*, Proc. ION GPS-01, Salt Lake City, Utah, Sept. 11-14, 2001
- EISSFELLER B.: *Das Europäische Satellitennavigationssystem GALILEO*. Proc. 4. SAPOS-Symposium, 21.-23.05.2002, Hannover, pp. 214-226.
- EISSFELLER B., HEIN G. W., WINKEL J., HARTL PH., VAN DIEREN-DONCK A. J.: *Requirements on the Galileo Signal Structure*. GNSS' 2000, Royal Institute of Navigation, Edinburgh, Scotland, May 1-4, 2000
- EISSFELLER B., TIBERIUS C., PANY T., BIBERGER R., SCHUELER T., HEINRICHSG.: *Instantaneous Ambiguity Resolution for GPS/Galileo RTK Positioning*. Journal for Gyroscopy and Navigation (translated to Russian) No. 3(38), 2002, pp. 71-91.
- EISSFELLER B., TIBERIUS C., PANY T., HEINRICH G.: *Real-Time Kinematic in the Light of GPS Modernisation and Galileo*. Galileo's World, Autumn 2002, pp. 28-34
- EISSFELLER B., TIBERIUS C., PANY T., BIBERGER R., SCHUELER T., HEINRICH G.: *Instantaneous Ambiguity Resolution for GPS/Galileo RTK Positioning*. Proc. of the 9th Saint Petersburg International Conference on Integrated Navigation Systems, Russia, St. Petersburg, 27-29 May, 2002, pp.: 72-86.
- ENGLER E., NOACK T., SCHLÜTER S.: *First Impression of GALILEO Performance derived with the Simulation Tool NavSim*, Proc. of GNSS 2001, Sevilla, Spain
- FALCK C., FLECHTNER F., MASSMANN F.-H., RAIMONDO J. C., TEUBEL A.: *Betrieb des PRARE-Bodensegmentes fuer ERS-2*; GFZ Potsdam, STR 99/22, Scientific Technical Report, 1999
- FERRO-FAMIL L., REIGBER A., POTTIER E., BOERNER W. M.: *Multi-Based Polarimetric SAR Data Classification using the Complex Wishart Distribution and Principal Component Analysis*, Proceedings of IGARSS'2001, Sydney, 2001.
- FERRO-FAMIL L., REIGBER A., POTTIER E., BOERNER W. M.: *Scene Characterization Using Sub-Aperture Polarimetric*

- SAR Data Analysis*. Proceedings of IGARSS'2002, Toronto, pp. 417-419, 2002
- FERRO-FAMIL L., REIGBER A., POTTIER E.: *Sub-Aperture Polarimetric SAR Data Analysis*, Proceedings of EUSAR'2002, Köln, pp. 725-728, 2002
- FREY S., MEYER U., FEJES I., PARAGI Z., CHARLOT P., BIANCALE R.: *Geodetic space VLBI: the first test observations*. In: *Advances in Space Research*, 2001.
- GALAS R., KOEHLER W.: *A binary exchange format for GPS data*, *Physics and Chemistry of the Earth*, Volume 26/6-8, 645-648, 2001
- GALAS R., WICKERT, J., BURGHARDT W.: *High rate low latency GPS ground tracking network for CHAMP*; *Physics and Chemistry of the Earth*, Volume 26/6-8, 649-652, 2001
- GILL E., MONTENBRUCK O.: *Spaceborne Autonomous Navigation for BIRD Satellite Mission*. Proc. 1st ESA Workshop on On-Board Autonomy, Oct. 17-19, 2001, ESTEC, Noordwijk, NL.
- GILL E., NAASZ B., EBINUMA T.: *First Results from a Hardware-in-the-Loop Demonstration of Closed-Loop Autonomous Formation Flying*; 26th Annual AAS Guidance and Control Conference, 5-9 Feb. 2003, Breckenridge, Colorado, 2003
- GRAFAREND E. W., SHAN J.: *GPS solutions: closed forms, critical and special configurations of P4P*, *GPS Solutions* 5, 29-41, 2002
- GRAFAREND E. W.: *Mixed integer-real valued adjustment (IRA) problems: GPS initial cycle ambiguity resolution by means of the LLL algorithm*, *GPS Solutions* 4, 31-44, 2000
- GRAFAREND E. W., AWANGE J. L.: *Determinations of vertical deflections by GPS/ LPS measurements*, *Zeitschrift für Vermessungswesen* 8, 279-288, 2000
- GUILLASO S., REIGBER A., POTTIER E.: *Amélioration de la résolution radiale d'images SAR aéroportées en utilisant des trajectoires parallèles multiples*, Proceedings of the 12^{ième} Journées Nationales Microondes, 16.-18.5.2001, Poitiers, 2001.
- GUILLASO S., FERRO-FAMIL L., REIGBER A., POTTIER E.: *InSAR Phase Unwrapping: A Polarimetric Approach*, Proceedings of RADAR'2002, Edinburgh, 2002
- HAAS R., GUEGUEN E., SCHERNECK H.-G., NOTHNAGEL A., CAMPBELL J.: *Crustal motion results derived from observations in the European geodetic VLBI network*. *Earth Planets Space*, Vol. 52 (No. 10), p. 759-764, 2000.
- HAJNSEK I., PAPPATHANASSIOU K. P., REIGBER A., CLOUDE S. R.: *Soil-Moisture Estimation Using Polarimetric SAR Data*, Proceedings of IGARSS'99, Hamburg, pp. 2440-2442, 1999
- HASE H.: *Phase Centre Determinations at GPS-Satellites with VLBI*, Proceedings of the 13th Working Meeting on European VLBI for Geodesy and Astrometry, held at Viechtach, February 12-13, 1999, edited by W. Schlüter and H. Hase, Bundesamt für Kartographie und Geodäsie, Wetzell, 1999
- HASE H.: *Theorie und Praxis globaler Bezugssysteme*, *Mitteilungen des BKG*, Band 13, 1999
- HASE H.: *Transportable Integrated Geodetic Observatory*, IVS Annual Report 1999, S. 110-115, NASA/TP-1999-209243, Sept. 1999
- HASE H.: *Transportable Integrated Geodetic Observatory*, IVS Annual Report 2000
- HASE H., BÖER A., RIEPL S., CARVACHO E., CECIONI A.: *Status of the TIGO-Project*, IVS Annual Report 2001
- HASE H., BÖER A., RIEPL S., SCHLÜTER W.: *TIGO – Ein bedeutender Beitrag der FGS zur Verbesserung globaler Bezugssysteme*, Begutachtung FGS, Kötzing, 28.-30.06.2000
- HASE H., BÖER A., RIEPL S., SCHLÜTER W.: *Transportable Integrated Geodetic Observatory (TIGO)*, IVS-GM-Proceedings, Kötzing, Febr. 2000
- HASE H., BÖER A., RIEPL S., SCHLÜTER W., CECIONI A.: *TIGO – Transportable Integrated Geodetic Observatory*, VI Congreso Intern. de Ciencias de la Tierra, Santiago de Chile, Aug. 7-11, 2000
- HASE H., BÖER A., RIEPL S., SCHLÜTER W., CECIONI A., BATAILLE K., AMTHAUER E., BARADIT E., NARVÁEZ A., CIFUENTES O.: *The TIGO-Project*, *ASP Conference Series*, Gyeong-ju Korea 2003
- HASE H., PETROV L.: *The First Campaign of Observations with the VLBI-Module of TIGO*, Proceedings of the 13th Working Meeting on European VLBI for Geodesy and Astrometry, held at Viechtach, February 12-13, 1999, edited by W. Schlüter and H. Hase, Bundesamt für Kartographie und Geodäsie, Wetzell, 1999
- HASE H., SCHLÜTER W., BÖER A.: *TIGO and its future application for the ITRF*, Proceedings of the International Workshop on Geodetic Measurements by the collocation of Space Techniques on Earth (GEMSTONE) January 25-28, 1999, Koganei, Tokyo/Japan
- HEIN G., GODET J., ISSLER J.-L., MARTIN J.-C., ERHARD P., LUCAS-RODRIGUEZ R., PRATT T.: *Status of Galileo Frequency and Signal Design*, Proc. ION-GPS 2002, Portland, 2002
- HEIN G. W.: *From GPS and GIONASS via EGNOS to Galileo Positioning and Navigation in the Third Millennium*. *GPS Solution*, Vol. 3, No. 4, pp. 39-47, April 17, 2000
- HEIN G. W., EISSFELLER B., WINKEL J., HARTL PH.: *Galileo Signal Options after WRC 2000*. *Galileo's World*, Summer 2000, pp. 24-31
- HEIN G. W., EISSFELLER B., WINKEL J., HARTL PH., VAN DIEREN-DONCK A. J.: *Requirements on the Galileo Signal Structure*. *ION GPS 2000*, 13th Int. Technical Meeting, Salt Lake City, Utah, USA, Sept. 19-22, 2000
- HEIN G. W., GODET J., ISSLER J., MATIN J., LUCAS-RODRIGUES R., PRATT T.: *The Galileo Frequency Structure and Signal Design*, Proc. ION GPS-01, Salt Lake City, Utah, Sept. 11-14, 2001
- HEIN G. W., ZINK T., EISSFELLER B.: *Integrity Monitoring Concepts for a Global Navigation Satellite System (GNSS-2)*. ION GPS '99, 12th Int. Technical Meeting, Nashville, Tennessee, USA, Sept. 14-17, 1999
- HEIPKE C., KOCHA., LOHMANN P.: *Analysis of SRTM DTM – Methodology and practical results*. *Journal der Schwedischen Gesellschaft für Photogrammetrie und Fernerkundung*, Nr. 2002:1, Photogrammetrie meets geoinformatics, Anders Boberg, Hsg., pp.69-80,2002
- HEISE S., JAKOWSKI N., WEHRENFENNIG A., REIGBER CH., LÜHR H.: *Sounding of the Topside Ionosphere/Plasmasphere Based on GPS Measurements from CHAMP: Initial Results*, *Geophys. Res. Lett.*, 29 (14), 10.1029/2002 GL014738, 2002.
- HEISE S., JAKOWSKI N., WEHRENFENNIG A., REIGBER C., LÜHR H.: *Initial Results on Ionosphere/Plasmasphere Sounding based on GPS Data Obtained On Board CHAMP*. In: C. REIGBER, H. LÜHR AND P. SCHWINTZER (Eds): *First CHAMP Mission Results for Gravity, Magnetic and Atmospheric Studies*, Springer-Verlag, 408-414, 2003.

- HELLWICH O., GÜNZL M., WIEDEMANN C.: *Fusion of Optical Imagery and SAR/INSAR Data for Object Extraction*. In: International Archives of Photogrammetry and Remote Sensing, XIXth International Congress ISPRS 2000, Amsterdam/NL (16-23 July 2000), Gopher Publishers, Groningen, Commission III, Vol. XXXIII, B3/1, p. 389-396. In: CD Geoinformation For All, XIXth International Congress ISPRS 2000, Amsterdam/NL (16-23 July 2000), GITC B.V., Commission III, CD 1.
- HELLWICH O., EBNER H.: *Geocoding SAR-Interferograms by Least Squares Adjustment*. In: ISPRS Journal for Photogrammetry and Remote Sensing, Elsevier Science B.V., Amsterdam/NL, Vol. 55, (2000), No. 4, p. 277-288.
- HELLWICH O., GÜNZL M., WIEDEMANN C.: *Landuse Classification by Fusion of Optical and Multitemporal SAR Imagery*. In: International Geoscience and Remote Sensing Symposium, Honolulu (24-28 July 2000), IEEE, Piscataway (2000), p. 2435-2437.
- HELLWICH O., GÜNZL M., WIEDEMANN C.: *Fusion of SAR/INSAR Data and Optical Imagery for Landuse Classification*. In: EUSAR 2000, 3rd European Conference of Synthetic Aperture Radar, München (23.-25.5.2000), VDE Verlag, Berlin/Offenbach (2000), S. 655-658.
- HELLWICH O. M., GÜNZL M., WIEDEMANN C.: *Fusion of Optical Imagery and SAR/INSAR Data for Object Extraction*. In: International Archives of Photogrammetry and Remote Sensing, XIXth International Congress ISPRS 2000, Amsterdam/NL (16-23 July 2000), Gopher Publishers, Groningen, Commission III, Vol. XXXIII, B3/1, p. 389-396. In: CD Geoinformation For All, XIXth International Congress ISPRS 2000, Amsterdam/NL (16-23 July 2000), GITC B.V., Commission III, CD 1.
- HELLWICH O., REIGBER A., LEHMANN H.: *Sensor and Data Fusion Contest: Test Imagery to Compare and Combine Airborne SAR and Optical Sensors for Mapping*, Proceedings of IGARSS'2002, Toronto, pp. 82-84, 2002
- HOWIND J., BÖHRINGER M., MAYER M., KUTTERER H., LINDNER K., HECK B.: *Korrelationsstudien bei GPS-Phasenbeobachtungen*. In: Dietrich, R. (Hrsg.): Deutsche Beiträge zu GPS-Kampagnen des Scientific Committee on Antarctic Research (SCAR) 1995-1998. DGK B 310, München 2000, 201-205.
- IGARASHI K., ARMAND N., PAVELYEV A., REIGBER CH., WICKERT J., HOCKE K., BEYERLE G., MATYUGOV S., YAKOVLEV O.: *Application of small satellites for high precision measuring effects of radio wave propagation*. 3rd IAA Symposium, ed. by Röser, H., Wissenschaft und Technik Verlag Berlin, 43-48, 2001.
- ILLNER M.: *Investigations concerning the reliability and the external accuracy of GPS Real-Time Measurements*. Paper presented to the XXII FIG International Congress, April 19-26, 2002, Washington, DC, USA, published by Mira CD-ROM Publishing 314-776-666, 2002.
- IRSIGLER M., HEIN G. W., EISSFELLER B., SCHMITZ-PEIFFER A., KAISER M., HORNOSTEL A., HARTL P.: *Aspects of C-Band Satellite Navigation: Signal Propagation and Satellite Signal Tracking*. Proc. of the European Navigation Conference ENC-GNSS2002, Copenhagen, 27-30 May 2002
- IVS (1999): *International VLBI Service for Geodesy and Astronomy 1999 Annual Report*, NASA/TP-1999-209243, Greenbelt MD
- JAKOWSKI N., WEHRENPENNIG A., HEISE S., REIGBER CH., LÜHR H., GRUNWALDT L., MEEHAN T. K.: *GPS Radio Occultation Measurements of the Ionosphere from CHAMP: Early Results*, Geophys. Res. Lett., 29, 10.1029/2001GL014364, 2002.
- JAKOWSKI N., WEHRENPENNIG A., HEISE S., REIGBER C., LÜHR H.: *Status of Ionospheric Radio Occultation CHAMP Data Analysis and Validation of Higher Level Data Products*. In: C. REIGBER, H. LÜHR AND P. SCHWINTZER (Eds.): *First CHAMP Mission Results for Gravity, Magnetic and Atmospheric Studies*, Springer-Verlag, 462-472, 2003.
- KILGER R., BAUERNFEIND E., KRONSCHNABL G., SCHATZ R., SCHWARZ W., ZEITLHÖFLER R., ZERNECKE R.: *Station Report of the 20m Radiotelescope at Wettzell*, IVS-Annual Report 2000
- KOCH A., HEIPKE C.: *Quality Assessment of Digital Surface Models derived from the Shuttle Radar Topography Mission (SRTM)*. IEEE 2001 International Geoscience and Remote Sensing Symposium, July 9-13, University of New South Wales, Sydney (Australia), 2001.
- KOCH A., HEIPKE C., LOHMANN P.: *Analysis of SRTM DTM – Methodology and practical results*, Joint International Symposium on Geospatial Theory, Processing and Applications. Commission IV, Ottawa, Kanada, 2002
- KOCH A., HEIPKE C.: *Quality Assessment of Digital Surface Models derived from the Shuttle Radar Topography Mission (SRTM)*, IEEE 2001 International Geoscience and Remote Sensing Symposium, July 9-13, University of New South Wales, Sydney (Australia), 2001
- KOCH A., LOHMANN P.: *Quality Assessment and Validation of Digital Surface Models Derived from the Shuttle Radar Topography Mission (SRTM)*, Proceedings, ISPRS, Vol. XXXIII, Amsterdam, 2000
- KOCH A.: *Genauigkeitsanalyse Digitaler Geländemodelle für die Shuttle Radar Topography Mission (SRTM)*, Publikationen der Deutschen Gesellschaft für Photogrammetrie und Fernerkundung, Band 9, Jörg Albertz, Hrsg., pp. 237-244, 2000
- KÖNIG R., CHEN Z., REIGBER C., SCHWINTZER P.: *Improvement in global gravity field recovery using GFZ-1 satellite laser tracking data*, Journal of Geodesy, 73, 8, p. 398-406, 1999.
- KÖNIG R., S. ZHU CH. REIGBER K.-H. NEUMAYER H. MEIXNER R. GALAS G. BAUSTERT, P. SCHWINTZER: *CHAMP Rapid Orbit Determination for GPS Atmospheric Limb sounding*, Advances in Space Research, 30 (2), 289-293, 2002.
- KRONSCHNABL G., REINHOLD A., SCHWARZ W., WOJZIAK R.: *Geodetic Observatory O'Higgins – BKG's IVS Network Station in Antarctica in 2001*, Annual Report 2001, IVS Coordinating Center, Febr. 2002
- LEE J. S., PAPATHANASSIOU K. P., AINSWORTH T. L., M. R. GRUNES M. R., REIGBER A.: *A New Technique for Noise Filtering of SAR Interferogram Phase Images*, IEEE Transactions on Geoscience and Remote Sensing, Vol. 36, No. 5, pp. 1456-1465, 1998
- LEE J. S., GRUNES M. R., AINSWORTH T. L., PAPATHANASSIOU K. P., REIGBER A.: *Speckle Filtering of SAR Data for Polarimetric Interferometry Applications*, Proceedings of IGARSS'99, Hamburg, pp. 2203-2205, 1999
- LUDWIG R., HELLWICH O., STRUNZG., ROTH A., EDER K.: *Applications of Digital Elevation Models from SAR Interferometry for Hydrologic Modelling*. In: PFG Photogrammetrie/Fernerkundung/Geoinformation, Schweizerbart'sche Verlagsbuchhandlung Stuttgart, Heft 2/2000, S. 81-94.
- MARQUARDT C., LABITZKE K., REIGBER CH., SCHMIDT T., WICKERT J.: *An assessment of the quality of GPS/MET*

radio limb soundings during February 1997. Physics and Chemistry of the Earth, Part A, 26, 125-130, 2001.

- MARQUARDT C., SCHOELLHAMMER K., BEYERLE G., SCHMIDT T., WICKERT J., REIGBER C.: *Validation and Data Quality of CHAMP Radio Occultation Data*. In: C. REIGBER, H. LÜHR AND P. SCHWINTZER (Eds.): *First CHAMP Mission Results for Gravity, Magnetic and Atmospheric Studies*, Springer-Verlag, 384-396, 2003.
- MEYER U., CHARLOT P., BIANCALE R.: *GINS: A New Multi-Technique Software for VLBI Analysis*, IVS 2000 General Meeting Proceedings, S. 324-328, 2000.
- MICHEL G. W., ANGERMANN D., KLOTZ J., REIGBER CH., XIA Y., WANG R.: *Fault motion and strain accumulation with GPS and INSAR: Recent results from studies in Asia and S-America*. European Geophys. Society Newsletter, 103, 1999.
- MONTENBRUCK O., EBINUMA T., LIGHTSEY E. G., LEUNG S.: *A Real-time Kinematic Gps Sensor For Spacecraft Relative Navigation*; Aerospace Science And Technology 6 435-449 (2002).
- MONTENBRUCK O., GILL E.: *Ionospheric Correction for GPS Tracking of LEO Satellites*; The Journal of Navigation 55, 293-304 (2002).
- MÜLLER J., EGGER D., REICHHOF B., SCHNEIDER M., SCHREIBER U.: *Lunar Laser Ranging at its Best*. In: Towards an Integrated Global Geodetic Observing System (IGGOS), Proceedings of the IAG Section II Symposium, held in Munich/Germany, Oct. 5-9, 1998, IAG Symposia, Vol. 120, Springer Verlag, S. 161-164.
- MÜLLER J., NORDTVEDT K., SCHNEIDER M., VOKROUHLICKY D.: *Improved Determination of Relativistic Quantities from LLR*. In: Proceedings of the 11th Workshop on Laser Ranging Instrumentation, Deggendorf, 21.-25. Sept. 1998, Mitteilungen des Bundesamtes für Kartographie und Geodäsie, Band 10, S. 216-222, Frankfurt/Main, 1999.
- MÜLLER J.: *LLR*, ILRS Annual Report 1999, 2000.
- MÜSKENS A., K. BÖRGER M. SORGENTE J. CAMPBELL: *Comparison of MkIII and MkIV Correlation using a 4-station IRIS-S experiment*. Proc. of the 14th Working Meeting on European VLBI for Geodesy and Astrometry, Castel San Pietro Terme, 8-9 September 2000, Istituto di Radioastronomia del CNR, Bologna, p. 125-136, 2000.
- NEUBERT R.: *The Centre of Mass Corrections of Spherical Satellites*, Presentation to 12th International Workshop on Laser Ranging, Matera, Italy, 13-17 November, 2000.
- NEUBERT R., GRUNWALDT L., SESSELMANN G., STEINBACH M.: *Innovative Telescope System For Slr Proc. Of Laser Radar Ranging And Atmospheric Lidar Techniques Ii Florence Italy September 20-21 P. 2* 1999.
- NEUBERT R., L. GRUNWALDT H. FISCHER: *The new SLR Station of GFZ Potsdam: A Status Report*, Presentation to 12th International Workshop on Laser Ranging, Matera, Italy, 13-17 November, 2000.
- NEUSCH T., STIES M.: *Experimenting with Radar Backscattering Models Using E-SAR Imagery*; Proceedings of the International Geoscience and Remote Sensing Symposium (IGARSS'99), Hamburg, June 1999.
- NOTHNAGEL A., STEINFORTH CH.: *IVS Analysis Coordination; CSTG Bulletin No. 17*, Deutsches Geodätisches Forschungsinstitut, Munich, 84-90, 2002
- NOTHNAGEL A., BROMORZKI O., CAMPBELL J., MÜSKENS A., ROTTMANN H., ROTTMANN I.: *Comparison of the Output of Repeated MkIII and MkIV Correlation Results*. IVS General Meeting Proceedings, N.R. Vandenberg and K.S. Baver (eds.), Feb 4-7, 2002, Tsukuba, Japan, NASA/CP-2002-210002, p. 107-111, 2002
- PANY T., EISSFELLER B., WINKEL J.: *Analysis of the Ionospheric Influence on Signal Propagation and Tracking of Binary Offset Carrier (BOC) Signals for Galileo and GPS*. Proc. Of the 27 General Assembly of the International Union of Radio Science, Maastricht, August, 2002
- PANY T., IRSIGLER M., EISSFELLER B., WINKEL J.: *Code and Carrier Tracking Performance of a Future Galileo RTK Receiver*. Proceedings of the European Navigation Conference ENC-GNSS 2002, Copenhagen, 27-30 May 2002
- PAPATHANASSIOU K. P., REIGBER A., CLOUDE S. R.: *Vegetation and Ground Parameter Estimation using Polarimetric Interferometry, Part II: The Role of Polarisation*, Proceedings of CEOS'99, Toulouse, 1999
- PAPATHANASSIOU K. P., CLOUDE S. R., REIGBER A., BOERNER W. M.: *Multi-baseline Polarimetric SAR Interferometry for Vegetation Parameters Estimation*, Proceedings of IGARSS'2000, Honolulu, pp. 2762-2764, 2000.
- PAPATHANASSIOU K. P., REIGBER A., CLOUDE S. R.: *Vegetation and Ground Parameter Estimation using Polarimetric Interferometry, Part I: Parameter Inversion and Optimal Polarisation*, Proceedings of CEOS'99, Toulouse, 1999
- PAPATHANASSIOU K. P., CLOUDE S. R., REIGBER A.: *Single and Multi-baseline Polarimetric SAR Interferometry over Forested Terrain*, Proceedings of EUSAR'2000, Munich, pp. 123-126, 2000.
- PAVELYEV A. G. IGARASHI K., REIGBER CH., HOCKE K., WICKERT J., BEYERLE G., MATYUGOV S., KUCHERJAVENKOV A., PAVELYEV, D., YAKOVLEV O.: *First application of the radioholographic method to wave observations in the upper atmosphere*, Radio Sci., 37(3):1043, 10.1029/2000RS002501, 2002.
- PAVELYEV A. G. LIU Y. A., REIGBER CH., WICKERT J., IGARASHI K., HOCKE, K., HUANG C. Y.: *GPS radio holography as a tool for remote sensing of the atmosphere and mesosphere from space*, GPS Solutions, 6, 96-99, DOI: 10.1007/s10291-002-0022-6, 2002.
- POTSIS A. REIGBER A., MITTERMAYER J., MOREIRA A., UZUNOGLU N.: *Sub-aperture algorithm for motion compensation improvement in wide-beam SAR data processing*. IEE Electronic Letters, Vol. 37, No. 23, pp. 1405-1407, 2001
- POTSIS A., REIGBER A., MITTERMAYER J., MOREIRA A., UZUNOGLU N.: *Improving the Focusing Properties of SAR Processors for Wide-band and Wide-beam Low Frequency Imaging*, Proceedings of IGARSS'2001, Sydney, 2001.
- POTSIS A., A. REIGBER T. SUTOR K. P. PAPATHANASSIOU: *A Phase Preserving Method for RF Interference Suppression in P-Band Synthetic Aperture Radar Interferometric Data*, Proceedings of IGARSS'99, Hamburg, pp. 2655-2657, 1999
- POTSIS A., GABLER B., HORN R., PAPATHANASSIOU K. P., REIGBER A., MAKIOS V.: *End-to-End Calibration of Polarimetric P-band data of DLR Experimental SAR (E-SAR)*, Proceedings of EUSAR'2000, Munich, pp. 849-852, 2000.
- POTSIS A., REIGBER A., ALIVISATOS E., MOREIRA A., UZUNOGLU N.: *Comparison of Chirp Scaling and Wavenumber Domain Algorithms for Airborne Low-frequency SAR Data Processing*, Proceedings of SPIE'2002, Crete, 2002
- POTSIS A., REIGBER A., MOREIRA A., FERRO-FAMIL L., UZUNOGLU N.: *Comparison of Chirp Scaling and Wavenumber Domain Processing Algorithms for Airborne Low*

- Frequency SAR Data Processing*, Proceedings of EUSAR'2002, Köln, pp. 69-72, 2002
- REICH M., THIEL K. H.: *Vergleich von Digitalen Höhenmodellen*. Publikation der Deutschen Gesellschaft für Photogrammetrie und Fernerkundung. 22. Wissenschaftlich-Technische Jahrestagung der DGPF, Band 11 2002
- REIGBER A., MOREIRA A.: *First Demonstration of Airborne SAR Tomography using Multibaseline L-band Data*, IEEE Transactions on Geoscience and Remote Sensing, Vol. 38, No. 5, pp. 2142-2152, September 2000.
- REIGBER A.: *Range Dependent Spectral Filtering to Minimize the Baseline De-correlation in Airborne SAR Interferometry*. Proc. of IGARSS'99, Hamburg, pp. 1721-1723, 1999
- REIGBER A., MOREIRA A., PAPATHANASSIOU K. P.: *First Demonstration of Airborne SAR Tomography using Multibaseline L-band Data*, Proceeding of IGARSS'99, Hamburg, pp. 44-46, 1999
- REIGBER A., PAPATHANASSIOU K. P., CLOUDE S. R., MOREIRA A.: *SAR Tomography and Interferometry for Remote Sensing of Forested Terrain*, Proceeding of EUSAR'2000, Munich, pp. 137-140, 2000.
- REIGBER A., PAPATHANASSIOU K. P.: *Correction of residual motion errors in airborne repeat-pass interferometry*, Proceedings of IGARSS'2001, Sydney, 2001.
- REIGBER A., PAPATHANASSIOU K. P., CLOUDE S. R., MOREIRA A.: *SAR Tomography and Interferometry for Remote Sensing of Forested Terrain*, Frequenz – Die Zeitschrift für Telekommunikation, Vol. 55, pp. 119-122, 2001
- REIGBER A., SCHEIBER R.: *Differential SAR Interferometry Using an Airborne Platform*, Proceedings of EUSAR'2002, Köln, pp. 373-376, 2002
- REIGBER A.: *Airborne Polarimetric SAR Tomography*, DLR Forschungsbericht No. 2002-2, Doktorarbeit Universität Stuttgart, 2002
- REIGBER A.: *Correction of residual motion errors in airborne SAR interferometry*, IEE Electronic Letters, Vol. 37, No. 17, pp. 1083-1084, 2001
- REIGBER CH., ANGERMANN D., KLOTZ J., MICHEL G., PORTH R., SCHELLE H., XIA Y.: *Deformationsmessungen mit GPS und D-INSAR*. GeoForschungsZentrum Potsdam, Zweijahresbericht 1996/1997, 19-27, Potsdam, 1999.
- REIGBER CH., SCHWINTZER P., LÜHR H.: *The CHAMP geopotential mission*. Bolletino di Geofisica Teoretica ed Applicata, 40, 285-289, 1999.
- REIGBER CH., BALMINO G., SCHWINTZER P., BIANCALE R., BODE A., LEMOINE J.-M., KÖNIG R., LOYER S., NEUMAYER H., MARTY J.-CH., BARTHELMES F., PEROSANZ F., ZHU S. Y.: *A high-quality global gravity field model from CHAMP GPS tracking data and accelerometry (EIGEN-1S)*, Geophys. Research Letter, 29, No. 14, 10.1029/2002GL015064, 37-1 – 37-4, 2002.
- REIGBER CH., GALAS R., KÖNIG R., JAKOWSKI N., WICKERT J., WEHRENFENNIG A.: *GFZ and DLR contribution to GPS ground network supporting CHAMP mission*. RUMMEL, R. ET AL. (EDS.), *Towards an Integrated Global Geodetic Observing System*, Proc. IAG Symposia, 120, 222-224, Springer-Verlag Heidelberg, 2000.
- REIGBER CH., LÜHR H., SCHWINTZER P.: *Status of CHAMP mission*. RUMMEL, R. ET AL. (EDS.), *Towards an Integrated Global Geodetic Observing System*, Proc. IAG Symposia, 120, Springer-Verlag Heidelberg, 63-65, 2000.
- REIMER R.: *Zwischenpräsentation GLOMO*, Neustrelitz, 29.3.2000.
- RIEPL S.: *Experimental Verification of the MARINI-MURRAY Model by Two Colour SLR*, Matera, Laser Ranging Workshop 2000
- RIEPL S., SCHLÜTER W.: *Normal Point Algorithm for Reduction of two Colour SLR Observations*, 2001 Kluwer Academic Publishers, Netherlands, Surveys in Geophysics 00: 1-8, 2001
- RIEPL S., SCHREIBER U., SCHLÜTER W.: *Improvements of SLR by Adaptive Optics*. Proceedings of the 11th Workshop on Laser Ranging, p. 209-215, 1999.
- RIEPL S., SCHREIBER U., SCHLUETER W.: *Evaluation of an SLR adaptive optics system*, Proc. of Laser Radar Ranging and Atmospheric Lidar Techniques II, Florence, Italy, September 20-21, p. 2, 1999.
- RIEPL S., SCHREIBER U., SCHLÜTER W.: *Evaluation of an SLR Adaptive Optics System*. Proceedings of the SPIE, Vol. 3865, p. 90-95, 1999.
- ROTHACHER M.: *Towards an Integrated Global Geodetic Observing System* IAG-Symposium 120, R. Rummel, H. Drewes, W. Bosch, H. Hornik (eds.), p. 41-52, Springer Berlin, 2000
- RUMMEL R.: *Fortschritte der Satellitengeodäsie*. NRWakW, Vorträge: Natur-, Ingenieur- und Wirtschaftswissenschaften, N 453, S. 7-15, Westdeutscher Verlag, Wiesbaden, 2000.
- SEEGER H., SCHLÜTER W.: *Der Beitrag des IfAG/BKG zum europäischen Bezugssystem EUREF – Gründungsphase und Kampagnen – (Festschrift 50 Jahre IfAG/BKG, Juli 2002)*
- SCHEIBER R., REIGBER A., ULBRICHT A., PAPATHANASSIOU K. P., HORN R., BUCKREUSS, S., MOREIRA A.: *Overview of Interferometric Data Acquisition and Processing Modes of the Experimental Airborne SAR System of DLR*, Proceedings of IGARSS'99, Hamburg, pp. 35-37, 1999
- SCHLÜTER W.: *The International VLBI Service for Geodesy and Astrometry (IVS): Chairmans's Report*, AR-IVS, NASA/TP 1999-209243
- SCHLÜTER W.: *Die Aktivitäten der Fundamentalstation Wettzell*, DGK-Heft (DFG-Rundgespräch 2001/Höllenstein)
- SCHLÜTER W.: *IVS Chair's Report, Annual Report 2001*, IVS Coordinating Center, Febr. 2002
- SCHLÜTER W., DASSING R., KILGER R., SCHREIBER U.: *The Fundamental Station Wettzell – current status and future plans*, Proceedings of the International Workshop on Geodetic Measurements by the collocation of Space Techniques on Earth (GEMSTONE) January 25-28, 1999a, Koganei, Tokyo/Japan
- SCHLÜTER W., FEIL D., HESSELS U.: *Report: The Determination of differential time corrections for GPS time equipment employed at the Funamentalstation Wettzell and at TIGO*, July 2002
- SCHLÜTER W., HASE H., BÖER A.: *TIGO – a geodetic observatory for the improvement of the global reference frame; Prepared for the EOS/SPIE Symposium on Remote Sensing*, Sept. 20-24, 1999b, Florence/Italy, Proceedings of SPIE
- SCHLÜTER W., HASE H., BÖER A., RIEPL S., ALVAREZ J., CECIONI A.: *Progress of the TIGO-Project*, CSTG-Bulletin 16, München 2000
- SCHLÜTER W., HASE H., BÖER A., RIEPL S., CECIONI A.: *TIGO starts its operation in Concepción in 2002*, CSTG Bulletin 17, München, Sept. 2002

- SCHLÜTER W., HASE H., RÖTTCHER K., STÖGER R., LANG H., ZERNECKE R.: *Actual Results of the Local Survey at the FS-Wettzell*, Proceedings of GEMSTONE, Koganei, Tokio, January 25-28, 1999
- SCHLÜTER W., HAYO H., BÖER A., RIEPL S., ALVAREZ J., CECIONI A.: *Progress of the TIGO-Project*, Proceedings of the 4th Workshop, Shanghai, P.R. China, 14-19 May, 2001, (APSG 2001)
- SCHLÜTER W., HIMWICH E., NOTHNAGEL A., VANDENBERG N., WHITNEY A.: *IVS and its important Role in the Maintenance of the Global Reference Systems*, 2002 COSPAR, Vol. 30, No. 2, pp.145-150, 2002
- SCHLÜTER W., HIMWICH E., NOTHNAGEL A., VANDENBERG N., WHITNEY A.: *IVS and its important role in the maintenance of the global Reference System*, 33rd COSPAR Scientific Assembly Warsaw/PL, 16.-23. July 2001
- SCHLÜTER W., HIMWICH E., NOTHNAGEL A., VANDENBERG N., WHITNEY A.: *IVS and its important Role in the Maintenance of the Global Reference Systems*, COSPAR, Warsaw, Sept. 2000
- SCHLÜTER W., HIMWICH E., VANDENBERG N., NOTHNAGEL A., WHITNEY A.: *The International VLBI Service for Geodesy and Astrometry (IVS) – Two Years After its Implementation*, Proceedings of the 4th Workshop, Shanghai, P.R. China, 14-19 May, 2001, (APSG 2001)
- SCHLÜTER W., SCHUH H., VANDENBERG N.: *Evolving IVS Products and Related Observing Programs*, EGS-Proceedings special issue of Physics and Chemistry of the Earth, Elsevier-Verlag (April 2002), in preparation
- SCHLÜTER W., SEEGER H., BÖER A., DASSING R., HASE H., KLÜGEL T., KILGER R., REINHOLD A., RIEPL S., ROTHACHER M., SCHLICHT A., SCHREIBER U., WOJZDZIAK R.: *Die geodätischen Fundamentalstationen Wettzell und TIGO und die Antarktisstation O'Higgins*; Reihe BKG, 50 Jahre BKG (Juli 2002)
- SCHLÜTER W., VANDENBERG N.: *Geodetic VLBI – wishes and limitations*, New Technologies in VLBI Korea, ASP Conference Series, Gyeong-ju Korea 2003
- SCHLÜTER W., VANDENBERG N.: *Prospective Development of the International VLBI Service for Geodesy and Astrometry over the next few years*, CSTG-Bulletin Nr. 17, July 2002
- SCHLÜTER W., VANDENBERG N.: *International VLBI Service for Geodesy and Astrometry (IVS)*, CSTG-Bulletin 16, München 2000
- SCHLÜTER W., ZERNECKE R., KLÜGEL T.: *Local Survey at the FS-Wettzell*, EGS-Nice/F, EGS02-A-03965, 03.05.2002
- SCHLÜTER W., BOER A., HASE H.: *TIGO – a geodetic observatory for the improvement of the global reference frame*, Proc. of Laser Radar Ranging and Atmospheric Lidar Techniques II, Florence, Italy, September 20-21, p. 2, 1999.
- SCHMIDT R., G. BAUSTERT R. KÖNIG H. MEIXNER K.-H. NEUMAYER CH. REIGBER: *The Development of Automated Processing of Orbit Predictions for CHAMP*, Presentation to 12th International Workshop on Laser Ranging, Matera, Italy, 13-17 November, 2000.
- SCHREIBER U., HAUFE K. K., PROCHÁZKA I.: *Concept of a Pet4/labView-Control System*. Proceedings of the 11th Workshop on Laser Ranging, p. 413-420, 1999.
- SCHREIBER U., HAUFE K. H.: *Timewalk in Avalanche Photo Diodes*. Proceedings of the 11th Workshop on Laser Ranging, p. 445-451, 1999.
- SCHREIBER U., K. H. HAUFE: *Systematic biases in laser range measurements*, Proc. of Laser Radar Ranging and Atmospheric Lidar Techniques II, Florence, Italy, September 20-21, p. 2, 1999.
- SCHREIBER U., KAWANO N., YOSHINO T., DEGNAN J., NORDTVEDT K., MULLER J., SCHLÜTER W., KUNIMORI H.: *Laser ranging and VLBI for the SELENE II Mission*, Proc. International workshop on Geodetic Measurements by the collocation of Space Techniques ON Earth (Gemstone), pp. 131-136, Tokyo, Japan, January 25-28, 1999.
- SCHREIBER U., S. RIEPL A. SCHLICHT A. BOER R. DASSING: *The New Control System for WLRs and TIGO: Getting Started*, Presentation to 12th International Workshop on Laser Ranging, Matera, Italy, 13-17 November, 2000.
- SCHREIBER U., SCHLICHT A., HAUFE K. H.: *Systematic Biases on Laser Range Measurements*. Proceedings of the SPIE, Vol. 3865, p. 64-73, 1999.
- SCHREIBER U.: *(Habilitationsschrift) Ringlasertechnologie für geowissenschaftliche Anwendungen*, Mitteilungen des Bundesamtes für Kartographie und Geodäsie (Band 8)
- SCHREIBER U.: *How to improve SLR?*, Presentation to 12th International Workshop on Laser Ranging, Matera, Italy, 13-17 November, 2000.
- SCHREIBER U.: *Summary from the Colloquium on SLR-System Calibration Issues (Invited)*, Presentation to 12th International Workshop on Laser Ranging, Matera, Italy, 13-17 November, 2000.
- SCHREIBER U., KAWANO N., YOSHINO T., DEGNAN J., NORDTVEDT K., MÜLLER J., SCHLÜTER W., KUNIMORI H.: *Laser Ranging and VLBI for the Selene-II Mission*, Proceedings of the International Workshop on Geodetic Measurements by the collocation of Space Techniques on Earth (GEMSTONE) January 25-28, 1999, Koganei, Tokyo/Japan
- SCHREIBER U., KLÜGEL T., STEDMAN G. E., SCHLÜTER W.: *Stabilitätsbetrachtungen für große Ringlaser*, DGK-Heft (DFG-Rundgespräch 2001/Höllensteinsee)
- SCHREIBER U., SCHNEIDER M., ROWE C. H., STEDMAN G. E., SCHLÜTER W.: *Stabilising the Operation of a Large Ring Laser*, Symposium Gyro Technology, 14./15.09.1999, Stuttgart, Germany, Proceedings of the Symposium on Gyro Technology, Stuttgart 1999, Seite 14.0-14.10
- SCHREIBER U., SCHNEIDER M., ROWE C. H., STEDMAN G. E., COOPER S. J., SCHLÜTER W., SEEGER H.: *The C-II Ring Laser Project*, published by Elsevier Science Ltd., Phys. Chem. Earth (A), Vol 25, No. 12, pp. 805-807, 2000
- SCHREIBER U., SCHNEIDER M., ROWE C. H., STEDMAN G. E., SCHLÜTER W.: *Aspects of Ring Lasers as local Earth Rotation Sensors*, Surveys in Geophysics 22: 603-611, 2001
- SCHREIBER U., SCHNEIDER M., STEDMAN G., SCHLÜTER W.: *Characteristics of a Ring Laser for Geodesy*, Proceedings of the 13th Workshop Meeting on European VLBI, 278-284, 1999
- SCHREIBER U., SCHNEIDER M., STEDMAN G. E., ROWE C. H., SCHLÜTER W.: *Characterisation of the C-II Ring Laser*, Paper eingereicht im Febr. 2001 zur Publikation in: "Lecutre Notes", Springer Verlag, Editor Grafarend
- SCHREIBER U., SCHNEIDER M., STEDMAN G. E., HASSELBACH F., RUDER H., SCHLÜTER W.: *Inertial Sensors for the Precise Measurement of Earth Rotation*, Proceedings of the Journées 1999, Systems de reference, Dresden 1999
- SCHREIBER U., SCHNEIDER M., STEDMAN G. E., ROWE C. H., SCHLÜTER W.: *Charakterisierung des C-II Ringlasers*, Schriftenreihe der Institute des Studienganges Geodäsie und Geoinformatik, Stuttgart, Report 1999, 6-2 S. 433-438 (Stuttgart, 1999)

- SCHREIBER U., SCHNEIDER M., STEDMAN G. E., ROWE C. H., SCHLÜTER W.: *Der C-II Ringlaser als Prototyp eines Rotationssensors für geowissenschaftliche Anwendungen*, Mitteilungen des Bundesamtes für Kartographie und Geodäsie (Band 5), zusammengestellt von Manfred Schneider (1999)
- SCHREIBER U., VELIKOSELTSEV A., KLÜGEL T., STEDMAN G. E., SCHLÜTER W.: Advances in the Stabilization of large Ring Laser Gyroscopes, Symposium "Gyro Technology", Stuttgart, 2001
- SCHUH H., SCHLÜTER W., VANDENBERG N.: *Prospective Improvements of IVS Products and Evolvement of Observing Programs*, Proceedings of Journee 2002, Bukarest, Rumänien 2002
- SCHWEIKERT R., T. WÖRZ R. DE GAUDENZI A. STEINGASS: *On Signal Structures for GNSS2*, International Journal of Satellite Communications Vol.18 Nr. 4 & 5, July-October 2000
- SCHWINTZER P., REIGBER CH.: *The contribution of GPS flight receivers to global gravity field recovery*, Journal of Global Positioning Systems, 1, 61-63, 2002.
- STEINGASS A.: *High Precision Algorithm for Phase Estimates*, Proc. of GNSS 2001, Sevilla, Spain
- STEINGASS A.: *Pulse Shape Selection for Navigation Systems in a Multipath environment*, National Technical Meeting of the Institute of Navigation NTM- ION 2001, Long Beach CA USA
- STEINGASS A., A. DAMMANN M. ANGERMANN R. SCHWEIKERT T. WÖRZ: *The Impact of High Power Amplifiers and their associated Lowpass filters on Pseudorange accuracy and the spectrum of the Signal*, Proc.of GNSS 2000, Edinburgh, Great Britain
- STIES M., HAGG W.: *Verarbeitung und Klassifizierung von SAR-Satellitenbilddaten*; in J. Albertz, S. Dech (Hrsg.): *Photogrammetrie und Fernerkundung – Globale und lokale Perspektiven*, Publikationen der Deutschen Gesellschaft für Photogrammetrie und Fernerkundung, Band 7, 1999
- TIBERIUS C., PANY T., EISSFELLER B., DE JONG K., JOOSTEN P., VERHAGEN S.: *Integral GPS-Galileo Ambiguity Resolution*. Proc. ENC-GNSS 2002, Copenhagen, 2002.
- TIBERIUS C., PANY T., EISSFELLER B., JOOSTEN P., VERHAGEN S.: *0.99999999 Confidence Ambiguity Resolution with GPS and Galileo*. GPS Solutions 6, 2002, pp. 96-99.
- ULBRICHT A., REIGBER A., HORN R., POTSIS A., MOREIRA A.: *Multi-Frequency SAR-interferometry: DEM-generation in L- and P-band and vegetation height estimation in combination with X-band*, Proceedings of EUSAR'2000, Munich, pp. 51-54, 2000.
- ULBRICHT A., REIGBER A.: *L-Band Repeat-Pass DEM-Generation with DLR's Experimental SAR (E-SAR)*, Proceedings of IGARSS'99, Hamburg, pp. 2164-2166, 1999
- WEBER T., TRAUTENBERG H. L., SCHÄFER CHR.: *Galileo System Architecture – Status and Concepts*, Proceedings ION GPS 2001, Salt Lake City.
- WICKERT J., SCHMIDT T., MARQUARDT C., REIGBER CH., NEUMAYER K.-H., BEYERLE G., GALAS,R., GRUNWALDT L.: *GPS radio occultation with CHAMP: First results and status of the experiment*. In: *Vistas for Geodesy in the New Millenium*, Proc. IAG Symposia, 125, Springer-Verlag, 273-278, 2002.
- WICKERT J., BEYERLE G., HAJJ GEORGE A., SCHWIEGER V., REIGBER CH.: *GPS radio occultation with CHAMP: Atmospheric profiling utilizing the space-based single difference technique*. Geophysical Research Letters, 10.1029/2001GLO13982, 2002.
- WICKERT J., GALAS R., BEYERLE G., KÖNIG R., REIGBER CH.: *GPS ground station data for CHAMP radio occultation measurements*. Physics and Chemistry of the Earth, Part A, 26, 503-511, 2001.
- WICKERT J., REIGBER CH., BEYERLE G., KÖNIG R., SCHMIDT T., GRUNWALDT L., GALAS R., MEEHAN T., MELBOURNE W., HOCKE K.: *Atmosphere sounding by GPS radio occultation: First results from CHAMP*. Geophysical Research Letters, 28, 3263-3266, 2001.
- XIA Y., REIGBER CH.: *Differential SAR-Interferometry for Monitoring Co- and Inter-Seismic deformation in Intofagasta Region*, IGARSS'99, Hamburg Germany, 28 June-2 July 1999, 74, 1999.
- XIA Y.: *Differential SAR-Interferometry for Monitoring Co- and Inter-Seismic deformation* EGS 24th General Assembly, The Hague, G3, 103, 1999.
- XIA Y., KAUFMANN H., GUO X.: *Landslide monitoring in the Three Georges Area using D-InSAR and corner reflectors*. Advanced Workshop on InSAR for Measuring Topography and Deformation of the Earths Surface (Hong Kong 2002), Dec. 16-17, Hong Kong, JLGIS-CAS-CUHK, 14-24, 2002
- YOSHINO T., KUNIMORI H., AMAGI J., SCHREIBER U., KAWANO N., KONDO T., SCHLÜTER W., DEGAN J.: *Lunar Laser Ranging by Optical Transponder Collocated vbi Radio Sources on the Moon*. Proceedings of the SPIE, Vol. 3865, p. 20-26, 1999.
- ZHU S. Y., MASSMANN F.-H., YU Y., REIGBER CH.: *Satellite Antenna Phase Center Errors in GPS Solutions*. Journal of Geodesy. Also pub. in GFZ STR01/12 (2001), pp.8-17, 2001
- ZHU S. Y., REIGBER CH., KANG Z., YU Y.: *Geocenter variations derived from GPS data*. IERS Tech. Note 25, pp.113-121, 1999
- ZINK T., EISSFELLER B., LÖHNERT E., WOLF R.: *Analyses of Integrity Monitoring Techniques for a Global Navigation Satellite System (GNSS-2)*. IAIN World Congress/U.S. ION Annual Meeting Receipt, Catamaran Hotel, San Diego, CA, USA, June 26-28, 2000
- ZINK T., HEIN G. W., EISSFELLER B.: *Integrity Monitoring Concepts for a Global Navigation Satellite System (GNSS-2)*. GNSS'99 3rd European Symposium, Genua, Italy, Oct. 5-8, 1999
- ZUMBERGE J., GENDT G.: *The demise of the selective availability and implications for the International GPS Service*, Physics and Chemistry of the Earth (A), Vol.26, No.6-8, pp.637-644, 2001

Atmosphere sounding using GPS radio occultation

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Introduction

On July 17, 1995 the U.S. Air Force announced ... *that today the Global Positioning System (GPS) satellite constellation has met all requirements for Full Operational Capability.* Apart from precise positioning GPS signals also can be used to derive characteristic properties of the propagation medium (neutral atmosphere and ionosphere).

Onboard the Low-Earth-Orbiting MICROLAB-1 satellite (launched on April 5, 1995) GPS signals were recorded, which were transmitted by a setting GPS satellite and tangentially travelled the Earth's atmosphere (GPS occultation measurements within the GPS/MET-Experiment, WARE et al., 1996). Globally distributed vertical profiles of atmospheric temperature, water vapour and electron density were successfully derived, the GPS radio occultation technique as an innovative remote sensing method became reality.

The properties of the calibration-free atmosphere limb sounding technique (e.g. all-weather-capability, high accuracy, high vertical resolution, low cost realization) offer great potential for atmospheric and ionospheric research, improvement of numerical weather forecasts, space weather monitoring and climate change detection (e.g. ANTHES et al., 2000; HAJJ et al., 2000; KUO et al., 2000; KURSINSKI et al., 1997).

Measurement principle

The GPS radio occultation technique is based on precise dual-frequency phase measurements (L-band; 1.2 and 1.5 GHz) of a GPS receiver in a Low-Earth-Orbit tracking a setting or rising GPS satellite. Combining these measurements with the satellites' position and velocity information, the phase path increase due to the atmosphere during the occultation event can be derived. A double difference technique is used to eliminate satellite clock errors: the signals from the occulting satellite are differenced with those from a reference GPS satellite. These satellite data then are synchronized with simultaneously recorded data, provided by a fiducial ground network. Details of the excess phase calibration are given by HAJJ et al. (2002), WICKERT (2002) or WICKERT et al. (2001b).

Atmospheric bending angles are derived from the time derivative of the calibrated atmospheric excess phase after appropriate filtering. The ionospheric correction is performed by linear combination of the L1 and L2 bending angle profiles (VOROB'EV and KRASILNIKOVA, 1994). Vertical profiles of atmospheric refractivity can be retrieved from the ionosphere

corrected bending angle profiles by Abel inversion. For dry air, the density profiles are obtained from the known relationship between density and refractivity. Pressure and temperature (*dry temperature*) are obtained from the hydrostatic equation and the equation of state for an ideal gas (e.g. MELBOURNE et al., 1994).

When water vapor is present, additional information is required to determine the humidity and density from refractivity profiles. Temperature profiles from operational meteorological analyses (e.g. of the European Centre for Medium-Range Weather Forecasts, ECMWF) are used to derive humidity profiles from the calculated refractivity in an iterative procedure (standard procedure, GORBUNOV and SOKOLOVSKIY, 1993). This algorithm suffers from a high sensitivity to even small errors in the analyses temperatures, resulting in large uncertainties of the derived water vapor profiles (MARQUARDT et al., 2001). More elaborate retrieval methods based on optimal estimation of both temperature and humidity including the error characteristics of the measurement and the *background* information (e.g. HEALY and EYRE, 2000) show more potential for obtaining water vapor profiles with high accuracy. More details of the derivation of atmospheric parameters from GPS radio occultation data are given by e.g. HOCKE (1997), KURSINSKI et al. (1997), or MELBOURNE et al. (1994)

GPS radio occultation with CHAMP

The German GPS radio occultation activities were started within the CHAMP satellite project (CHALLENGING Mini-satellite Payload, launch on July 15, 2000, REIGBER et al., 2003a) and the HGF strategy funds (German's Helmholtz Association's instrument of competition) project GASP (GPS Atmosphere Sounding Project, 1999-2002, REIGBER et al., 2003b; 1998). GASP was a project of the HGF centers AWI (Alfred Wegener Institut für Polar- und Meeresforschung), DLR (Deutsches Zentrum für Luft- und Raumfahrt), GKSS (Gesellschaft für Kerntechnik in Schiffbau und Schifffahrt) with GeoForschungsZentrum Potsdam (GFZ) as the project leading institution.

CHAMP, the German geoscience satellite, is in orbit and excellent condition now already for about 3 years (as of April 2003). In addition to measurements for the determination of the Earth's gravity and magnetic field, the data from a state-of-the-art GPS flight receiver (*BlackJack*, provided by Jet Propulsion Laboratory, JPL) are used to derive precise information about the vertical temperature, humidity and electron density distribution on a global scale using the GPS

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radio occultation technique (JAKOWSKI et al., 2002, WICKERT et al., 2001a).

Within GASP, beside GPS radio occultation as a space-based method, also the application of ground-based techniques for GPS atmosphere sounding (estimation of vertically integrated water vapour content with high accuracy) were evaluated (see e.g. REIGBER et al., 2002; DICK et al., 2001). The interdisciplinary research project combined the expertise of GPS experts, atmospheric physicists, meteorologists and climate experts. The main project goals were: installation of an infrastructure for the operational provision of space- and ground-based GPS atmospheric data and the assessment of their value for various applications in research and practice. For the first time continuous and rapid provision of GPS radio occultation data products (globally distributed vertical temperature profiles and atmospheric excess phases) with latencies between measurement and provision of 4-7 hours was demonstrated. Total water vapour content, derived from ground-based measurements at ~130 locations in Germany, is provided continuously with maximum delay of ~1.5 hours. Extensive validation studies with independent atmospheric/ionospheric data sets (meteorological analyses from ECMWF, radio sondes, ionosondes) were performed, techniques for assimilation of the GPS based atmospheric data were developed and applied (REIGBER et al., 2002).

Here the GPS radio occultation experiment aboard CHAMP is briefly focussed to. Together with the U.S. Argentinean SAC-C satellite (launched on November 21, 2000, HAJJ et al., 2003), CHAMP succeeds GPS/MET (1995-1997, ROCKEN et al., 1997). The measurements of both satellites and the improved (in relation to GPS/MET) infrastructure for GPS radio occultation data reception, transfer, analysis and provision brought significant progress for the GPS radio occultation technique.

CHAMP's GPS radio occultation experiment was activated on February 11, 2001. 7 occultation measurements during an one hour period were recorded by the GPS receiver onboard the satellite. Temperature and water vapour profiles were derived, the results were validated with meteorological analyses from ECMWF (WICKERT et al., 2001a). Already these early results have shown, that, in spite of the activated Anti-Spoofing (AS) mode of the GPS, CHAMP allows for precise atmospheric sounding. This became feasible by the use of the state-of-the-art GPS flight receiver (*BlackJack*, provided by JPL), combined with favourable antenna characteristics. The continuous availability of GPS occultation data is a significant progress in relation to GPS/MET (data analysis focussed to periods with de-activated AS, ROCKEN et al., 1997) and precondition for operational data processing and provision of atmospheric data, especially for applications within the numerical weather forecast. Further improvements are: first successful application of a space-based single differencing technique for precise occultation processing (WICKERT et al., 2002) and demonstration of using reduced ground station acquisition rates (in relation to the standard 1 Hz) for double difference occultation processing (WICKERT et al., 2003a). These improvements became feasible after the termination of the Selective Availability (SA) mode of the GPS on May 2, 2000 and simplifying the GPS occultation

processing. Using the radioholographic technique for the data analysis characteristic frequency shifts of direct and reflected GPS signals have been determined in the CHAMP observations. It was shown that these frequency shifts can be exploited to obtain information on ground elevation at the reflection point and ground-level refractivity (BEYERLE et al., 2002).

Within 578 days in 2001 and 2002 CHAMP recorded more than 118,000 occultations (duration >20s), about 74,000 vertical atmospheric profiles of good quality are provided to the scientific community via GFZ's Information System and Data Center for CHAMP (ISDC, <http://isdc.gfz-potsdam.de>). Since March 10, 2002 (update of the flight receiver software) ~260 measurements per day are performed. Since the CHAMP mission is estimated to last at least until 2007, an unprecedented long-term-set of GPS occultation data is expected.

The occultation measurements of CHAMP are also used to derive vertical profiles of electron density, a key parameter to characterize the ionosphere. These data contribute to operational data sets of the global electron density distribution for developing and improving global ionospheric models and to provide operational space weather information (e.g. HAJJ et al., 2000). The first 189 ionospheric radio occultations were performed on April 11 and 12, 2001 (JAKOWSKI et al., 2001). In total about 77,000 measurements were recorded during 2001 and 2002. More than 48,000 electron density profiles were derived and are provided via GFZ's data center (ISDC, <http://isdc.gfz-potsdam.de>) to the scientific community. Additional ionospheric information is derived from the GPS navigation measurements. An assimilation technique is applied to reconstruct 3D electron density distribution of the upper ionosphere and plasmasphere near the CHAMP orbit plane (HEISE et al., 2002).

Occultation infrastructure for CHAMP

The main components of the operational infrastructure for data generation, transfer, analysis and archiving are: the GPS receiver onboard the CHAMP satellite and the ground segment. It consists of the near polar downlink station at Ny Alesund, Spitsbergen (79.0°N, 11.5°E), the fiducial GPS ground network ('High Rate and Low Latency Network', Galas et al., 2001; currently consisting of about 40 stations), the Ultra rapid Precise Orbit Determination facility (KÖNIG et al., 2002), the operational occultation processing system and, for archiving and distribution, the CHAMP Information System and Data Center. A second downlink station at DLR Neustrelitz, Germany (53.1°N, 13.1°E) serves as backup. The GPS ground network is operated in cooperation between GFZ and JPL, the other components are maintained by GFZ.

Operational data analysis

At GeoForschungsZentrum Potsdam an operational data analysis system has been established to process satellite orbit data (KÖNIG et al., 2002), GPS ground station observations (WICKERT et al., 2001b) and radio occultation data in an operational manner (WICKERT et al., 2001a). The operational analysis of the ionospheric occultations is performed by DLR

Neustrelitz (JAKOWSKI et al., 2002; WEHRENFENNIG et al., 2001).

Validation and provision of atmospheric data

Vertical profiles of refractivity, dry temperature and water vapour were validated with ECMWF meteorological analysis and radio sonde data (BEYERLE et al., 2003b, SCHMIDT et al., 2003). Data, derived using earlier analysis software version were validated by MARQUARDT et al. (2003). The results indicate that stratospheric temperatures agree well with the analyses and sonde data. Between the upper troposphere and about 25 km altitude mean temperature deviations are <1 K and rms errors fall within the 2–4 K range. The biases at these heights could be either due to ECMWF or the CHAMP retrievals. A negative refractivity bias in the lower troposphere at low latitudes is observed in the CHAMP retrievals (AO et al., 2003). It can be significantly reduced by using a modified canonical transform method (BEYERLE et al., 2003a; GORBUNOV, 2002), which is not yet included in the operational data analysis. The quality of the derived water vapour profiles suffers from the observed negative refractivity bias, dry biases up to 30% at low latitudes were observed in relation to ECMWF.

The GPS occultation data of CHAMP and the results of the operational data analysis are provided via the CHAMP ISDC (<http://isdc.gfz-potsdam.de/champ/>). Information about the status of the operational occultation processing can be found at the homepage of the GPS Atmosphere Sounding project, hosted by GFZ: http://www.gfz-potsdam.de/pb1/GASP/GASP2/index_GASP2.html.

The currently available data and analysis results are: GPS occultation measurements from CHAMP (neutral atmosphere and ionosphere), GPS ground station data of the fiducial network, the GPS and CHAMP orbit ephemeris, occultation tables, atmospheric excess phases for each occultation event, vertical atmospheric parameters (temperature/water vapour), vertical electron density profiles and relative TEC (Total Electron Content) data of the ionosphere occultation satellite link.

Summary and outlook

The innovative GPS radio occultation technique for precise sounding of the Earth's atmosphere was established in Germany within the CHAMP satellite mission and the GPS Atmosphere Sounding Project (GASP). The radio occultation experiment aboard CHAMP brought significant progress for the GPS occultation technique. About 200 globally distributed vertical profiles of temperature and water vapour daily are provided via the CHAMP data center in an operational manner. Since the CHAMP mission is estimated to last at least until 2007, an unprecedented long-term-set of GPS occultation data is expected. The preparation of the future multi-satellite occultation missions profits from the CHAMP data. These missions are: ACE+ (Atmosphere and Climate Explorer; HOEG and KIRCHENGAST, 2002), COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate; ANTHES et al., 2000) or METOP (METeorology Operational; EDWARDS and PAWLAK, 2000; LOISELET et al.,

2000). These missions will operationally provide up to ~5,000 (for ACE+) precise and globally distributed vertical atmospheric profiles daily and will establish the GPS occultation technique as a standard method for remote sensing of the Earth's atmosphere on a global scale.

References

- ANTHES R. A., C. ROCKEN, Y. H. KUO: *Applications of COSMIC to Meteorology and Climate*, Terrestrial, Atmospheric and Oceanic Sciences, 11, 115-156, 2000.
- AO C. O., T. K. MEEHAN, G. A. HAJJ, A. J. MANNUCCI, G. BEYERLE: *Lower-Troposphere Refractivity Bias in GPS Occultation Retrievals*, J. Geophys. Res., submitted, 2003.
- BEYERLE G., M. E. GORBUNOV, C. O. AO: *Simulation studies of GPS radio occultation measurements*, Radio Sci., submitted, 2003a.
- BEYERLE G., J. WICKERT, CH. REIGBER, T. SCHMIDT, C. MARQUARDT, R. GALAS, L. GRUNWALDT, R. KÖNIG, T. K. MEEHAN, T. P. YUNCK: *The radio occultation experiment aboard CHAMP (Part II): Advanced retrieval techniques in atmospheric sounding and GPS reflectometry*, Proc. Int-Workshop on GPS Meteorology, Jan 14-16, Tsukuba, Japan, in print, 2003b.
- BEYERLE G., K. HOCKE, J. WICKERT, T. SCHMIDT, C. MARQUARDT, CH. REIGBER: *GPS radio occultations with CHAMP: A radio holographic analysis of GPS signal propagation in the troposphere and surface reflections*, J. Geophys. Res., 10.1029/2001JD001402, 2002.
- DICK G., G. GENDT, CH. REIGBER: *First Experience with Near Real-Time Water Vapor Estimation in a German GPS Network*, Journal of Atmospheric and Solar-Terrestrial Physics, 63, 1295-1304, 2001.
- GALAS R., J. WICKERT, W. BURGHARDT: *High rate low latency GPS Ground Tracking Network for CHAMP*, Phys. Chem. Earth (A), 26, 649-652, 2001.
- GORBUNOV M. E.: *Canonical transform method for processing radio occultation data in the lower troposphere*, Radio Sci., 37, 5, 1076, 2000RS002592, 2002.
- GORBUNOV M. E., S. V. SOKOLOVSKIY: *Remote sensing of refractivity from space for global observations of atmospheric parameters*, Report 119, Max Planck Institut für Meteorologie, Hamburg, 1993.
- HAJJ G. A., C. O. AO, B. A. IJIMA, D. KUANG, E. R. KURSINSKI, A. J. MANNUCCI, T. K. MEEHAN, L. J. ROMANS, M. DE LA TORRE JUÁREZ, T. P. YUNCK: *CHAMP and SAC-C atmospheric occultation results and intercomparisons*, J. Geophys. Res., submitted, 2003.
- HAJJ G. A. E. R. KURSINSKI, L. J. ROMANS, W. I. BERTIGER, S. S. LEROY: *A Technical Description of Atmospheric Sounding by GPS Occultations*, J. of Atmosphere and Solar-Terrestrial Physics, 64, 451-469, 2002.
- HAJJ G. A., L. C. LEE, X. PI, L. J. ROMANS, W. S. SCHREINER, P. R. STRAUS, C. WANG: *COSMIC GPS Ionospheric Sensing and Space Weather*, Terrestrial, Atmospheric and Oceanic Science, 11, 235-272, 2000.
- HEALY S. B., J. R. EYRE: *Retrieving temperature, water vapour and surface pressure information from refractive-index profiles derived by radio occultation data: A simulation study*, Q. J. R. Meteorol. Soc., 126, 1661-1683, 2000.
- HEISE S., N. JAKOWSKI, A. WEHRENFENNIG, CH. REIGBER, H. LÜHR: *Sounding of the Topside Ionosphere/Plasmasphere Based on GPS Measurements from CHAMP: Initial Results*,

- Geophys. Res. Lett., 29 (14), 10.1029/2002GL014738, 2002.
- HOCKE K.: *Inversion of GPS meteorology data*, Annales Geophysicae, 15, 443-450, 1997.
- HOEG P., G. KIRCHENGAST: *ACE+ Atmosphere and Climate Explorer Based on GPS, GALILEO, and LEO-LEO Radio Occultation*, Wissenschaftl. Ber. No. 14, 121pp., Inst. for Geophys., Astrophys., and Meteorology, Univ. of Graz, Austria, 2002.
- JAKOWSKI N., A. WEHRENFENNIG, S. HEISE, CH. REIGBER, H. LÜHR, L. GRUNWALDT, T. K. MEEHAN: *GPS Radio Occultation Measurements of the Ionosphere from CHAMP: Early Results*, Geophys. Res. Lett., 29(10), 10.1029/2001GL014364, 2002.
- KUO Y.-H., S. V. SOKOLOVSKIY, R. A. ANTHES, F. VANDENBERGHE: *Assimilation of GPS radio occultation data for numerical weather prediction*, Terrestrial, Atmospheric and Oceanic Sciences, 11, 157-186, 2000.
- KÖNIG R., S. ZHU, CH. REIGBER, K.-H. NEUMAYER, H. MEIXNER, R. GALAS, G. BAUSTERT, P. SCHWINTZER: *CHAMP Rapid Orbit Determination for GPS Atmospheric Limb Sounding*, Adv. Space Res., 30 (2), 289-293, 2002.
- KURSINSKI E. R., G. A. HAJJ, J. T. SCHOFIELD, R. P. LINFIELD, K. R. HARDY (1997): *Observing Earth's atmosphere with radio occultation measurements using the Global Positioning System*, J. Geophys. Res., 102, 23429-23465.
- LOISELET M., N. STRICKER, Y. MENARD, J. P. LUNTAMA: *GRAS – Metop's GPS-Based Atmospheric Sounder*, ESA Bulletin, 102, 38-44, 2000.
- MARQUARDT C., K. SCHÖLLHAMMER, G. BEYERLE, T. SCHMIDT, J. WICKERT, CH. REIGBER: *Validation and data quality of CHAMP radio occultation data*, Proc. of First CHAMP Science User Meeting, Springer Series, in print, 2003.
- MARQUARDT C., K. LABITZKE, CH. REIGBER, T. SCHMIDT, J. WICKERT: *An assessment of the quality of GPS/MET radio limb soundings during February 1997*, Phys. Chem. Earth (A), 26, 125-130, 2001.
- MELBOURNE W. G, E. DAVIS, C. DUNCAN, G. A. HAJJ, K. HARDY, E. KURSINSKI, T. MEEHAN, L. YOUNG: *The application of spaceborne GPS to atmospheric limb sounding and global change monitoring*, Publication 94-18, Jet Propulsion Laboratory, Pasadena, California, 1994.
- REIGBER CH. et al.: *CHAMP Project Site*, Internet: <http://www.gfz-potsdam.de/champ>, 2003a.
- REIGBER CH. et al.: *GASP Project Site*, Internet: <http://www.gfz-potsdam.de/pb1/GASP>, 2003b.
- REIGBER CH, G GENDT, G DICK, M TOMASSINI: *Near-real-time water vapor monitoring for weather forecasts*, GPS-World, 13, 18-27, 2002.
- REIGBER CH. et al.: *GPS Atmosphere Sounding – An innovative approach for the recovery of atmospheric parameters*, HGF Strategy fund proposal, Potsdam, Germany, 1998.
- ROCKEN, C., R. ANTHES, M. EXNER, D. HUNT, S. SOKOLOVSKIY, R. WARE, M. GORBUNOV, W. SCHREINER, D. FENG, B. HERMANN, Y.-H. KUO, X. ZOU: *Analysis and validation of GPS/MET data in the neutral atmosphere*, J. Geophys. Res., 102, 29849-29866, 1997.
- SCHMIDT T., J. WICKERT, C. MARQUARDT, G. BEYERLE, CH. REIGBER, R. GALAS, R. KÖNIG: *GPS Radio occultation with CHAMP: An innovative remote sensing method of the atmosphere*, Adv. Space Research, in print, 2003.
- WARE R., M. EXNER, D. FENG, M. GORBUNOV, K. HARDY, B. HERMAN, Y. KUO, T. MEEHAN, W. MELBOURNE, C. ROCKEN, W. SCHREINER, S. SOKOLOVSKIY, F. SOLHEIM, X. ZOU, R. ANTHES, S. BUSINGER, K. TRENBERTH: *GPS sounding of the atmosphere from low earth orbit: Preliminary results*, Bull. Am. Meteorol. Soc., 77, 19-40, 1996.
- WEHRENFENNIG A., N. JAKOWSKI, J. WICKERT: *A Dynamically Configurable System for Operational Processing of Space Weather Data*, Phys. Chem. Earth (C), 26, 601-604, 2001.
- VOROBEV V. V., T. G. KRASIL'NIKOVA: *Estimation of the accuracy of the atmospheric refractive index recovery from doppler shift measurements at frequencies used in the NAVSTAR system*, Phys. of the Atmosphere and Ocean, 29, 602-609, 1994.
- WICKERT J., R. GALAS, T. SCHMIDT, G. BEYERLE, CH. REIGBER, CH. FÖRSTE, M. RAMATSCHI: *Atmospheric sounding with CHAMP: GPS ground station data for occultation processing*, Phys. Chem. Earth, in print, 2003a.
- WICKERT J., R. KÖNIG, T. SCHMIDT, CH. REIGBER, N. JAKOWSKI, G. BEYERLE, R. GALAS, L. GRUNWALDT, T. K. MEEHAN, T. P. YUNCK: *The radio occultation experiment aboard CHAMP (Part I): Operational data processing*, technical aspects, atmospheric excess phase calibration and ionospheric profiling, Proc. Int- Workshop on GPS Meteorology, Jan 14-16, Tsukuba, Japan, in print, 2003b.
- WICKERT J.: *The CHAMP radio occultation experiment: Algorithms, Processing system, and First results* (in German), Scientific Technical Report 02/07, GFZ Potsdam, Germany, 2002.
- WICKERT J., G. BEYERLE, G. A. HAJJ, V. SCHWIEGER, CH. REIGBER: *GPS radio occultation with CHAMP: Atmospheric profiling utilizing the space-based single difference technique*, Geophys. Res. Lett., 29(8), 10.1029/2001GL013982, 2002.
- WICKERT J. CH. REIGBER, G. BEYERLE, R. KÖNIG, C. MARQUARDT, T. SCHMIDT, L. GRUNWALDT, R. GALAS, T. MEEHAN, W. MELBOURNE, K. HOCKE: *Atmosphere sounding by GPS radio occultation: First results from CHAMP*, Geophys. Res. Lett., 28, 3263-3266, 2001a.
- WICKERT J., R. GALAS, G. BEYERLE, R. KÖNIG., CH. REIGBER: *GPS ground station data for CHAMP radio occultation measurements*, Phys. Chem. Earth (A), 26, 503-511, 2001b.

Satellite Orbit Modelling

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Introduction

Due to the present and future satellite missions like CHAMP, GRACE, JASON-1, ENVISAT, ICESAT and GOCE, there is a considerable interest in high-precision satellite orbits these days. The remarkable contributions of German (and European) institutions to some of these new missions increases the number of groups and their efforts put into the processing of such data, including precise orbit determination (POD).

These satellite missions require high-precision orbits to reach their scientific goals (e.g. to study the components of the Earth's system and their interactions). In order to study, e.g., sea level change with altimetry, temporal variations of the gravity field with the gravity missions, or atmospheric sounding, the best possible orbit models and orbit determination strategies are needed. This is also true for the orbits of the GPS, GLONASS, and in future GALILEO.

Much progress has been achieved in the area of POD in the last few years, not the least because various new measurement types became available like accelerometers, star sensors, inter-satellite links, and much improved tracking receivers for GPS and DORIS.

This contribution summarizes the recent developments and advances in Germany in the field of satellite orbit modelling and orbit determination using various tracking systems.

Orbit Force Modelling Aspects

With the new satellite missions CHAMP, JASON-1, GRACE, GOCE, etc. the interest in the detailed modelling of the forces acting on LEOs (e.g. to account for the non-gravitational and the time-varying gravitational forces when determining the Earth's gravity field) has considerably increased. This can be seen from several diploma thesis that were written in this area. They study numerical integration methods (SCHMID, 1999), gravitational forces of Sun, Moon, and planets (PFISTER, 1999), atmospheric drag effects (KRAUS, 1998; HÄHNLE, 1999), and Earth albedo (JOHANNSEN, 1999). Also the visualization of satellite orbits was considered an important aspect (MANDEL and MÜLLER, 1999; NITSCHKE, 1999).

Other important aspects of the force modelling, like, e.g., the use of accelerometer data (SCHWINTZER et al., 2000) or new solar radiation pressure models for GPS satellites, will be outlined in the sections below.

Orbit Determination for GNSS

Accurate orbits (and clocks) of GPS satellite – of Global Navigation Satellites System (GNSS) satellites in general – are extremely important and a pre-requisite nowadays for a large variety of disciplines and GNSS applications. This is certainly the case for all fields, where high-precision positioning is an issue (geodynamic and geophysical studies concerning plate tectonics, Earthquakes, volcanoes, etc.) but also for GPS meteorology (estimation of integrated water vapor above GPS sites for climatology and weather forecasts), high-precision time and frequency transfer with GPS, Earth rotation studies and, not to be forgotten, kinematic or dynamic orbit determination of LEOs carrying one or more GPS (or GNSS) receivers.

Considerable improvements have been achieved in this field in the last few years: GPS satellite orbits and clocks routinely computed by the IGS analysis centers are now at a level of 2-3 cm and 100-150 ps, respectively. In Germany, mainly the GeoForschungsZentrum Potsdam (GFZ) and the European Space Agency (ESA) in Darmstadt, both Analysis Centers (AC) of the International GPS Service (IGS), are heavily and successfully involved in these IGS-related activities (GENDT et al., 2001; ZUMBERGE and GENDT, 2001; DOW et al., 2001; ROMERO et al., 2003). To achieve this accuracy, new solar radiation pressure models and parameterizations (SPRINGER et al., 1999) have been implemented in to the software packages. That the IGS is rapidly moving towards real-time orbits is discussed in one of the section below. Let us not forget to mention in this context, that for the computation of high-precision GPS satellite orbits and clocks, the phase center offsets and variations of the GPS satellite antennae have to be carefully corrected for. Contributions to this research topic are given in (ZHU et al., 2001; ROTHACHER et al., 2001; SCHMID et al., 2002; SHI et al., 2003).

Precise GLONASS orbits are also regularly computed by the Bundesamt für Kartographie und Geodäsie (BKG) and ESA (see, e.g., (ROMERO et al., 2002; INEICHEN et al., 1999)). Routinely, an orbit quality of about 10-20 cm is obtained by these analysis centers.

It is to be expected that in the near future new challenges in the orbit determination of GNSS satellites will come up with the new European GALILEO System, especially in Germany, which plays an important role in the GALILEO developments.

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Kinematic and Reduced-Dynamic Orbits of LEOs

With the new satellite missions CHAMP, SAC-C, JASON-1, GRACE and ICESAT, all carrying well-functioning GPS receivers, orbit determination has entered a new era. For the first time it has become possible to compute high-precision satellite positions for LEOs in a kinematic way, i.e., estimating the three coordinates of the satellite position and the correction of the LEO receiver clock epoch-by-epoch using the GPS code and/or phase measurements (XU, 2000; MONTENBRUCK, 2003; ROTHACHER and SVEHLA, 2002; SVEHLA and ROTHACHER, 2002, 2003). Such a kinematic POD approach is only possible with GPS tracking data today. Comparisons with SLR data and reduced-dynamic orbits indicate that kinematic orbits with an accuracy of about 2-3 cm can be computed for the CHAMP satellite. Kinematic POD should be seen as a complementary strategy to reduced-dynamic POD, because it allows to compute orbits completely independent of the satellite dynamics and force models. Kinematic orbits may thus help to validate force models for air drag, solar radiation pressure and the gravity field and may also serve as input data for gravity field determination (e.g., using the energy balance method). We refer to Section II; Satellite Gravity Field Missions and Section III; Global Gravity Field modelling for more information on this topic. (MONTENBRUCK, 2001) and (MONTENBRUCK et al., 2002) show that even with comparably cheap single-frequency GPS receivers a quite astonishing orbit quality can be achieved, when carefully correcting for the ionospheric delays.

Also reduced-dynamic POD with various orbit parameterizations are very successful for CHAMP (as well as for GRACE, as first results indicate). Strategies and results are documented in (NEUMAYER et al., 2000, 2003; KÖNIG et al., 2002). Additional topics relevant in the context of POD are treated in (KÖNIG et al., 2003 – CHAMP clock errors; KÖNIG and NEUMAYER, 2003 – thermospheric events; SVEHLA and ROTHACHER, 2003 – ambiguity resolution). An interesting study concerning the CHAMP GPS receiver performance may be found in (MONTENBRUCK et al., 2003).

A lot of very interesting orbit comparisons including various reduced-dynamic as well as kinematic approaches have recently been performed in the frame work of the IGS LEO Orbit Comparison Campaigns, which is the topic of the next section.

LEO Orbit Comparison Campaigns

As an initiative of the IGS LEO Working Group (chaired by ESA) – later joined by the Subcommittee on "Precise Orbit Determination for Low Earth Orbiting Satellites" of the Commission on International Coordination on Space Techniques for Geodesy and Geodynamics (CSTG) – a CHAMP orbit comparison campaign was set up in 2001 after the first CHAMP GPS data became freely available (BOOMKAMP et al., 2002; see also <http://nng.esoc.esa.de/gps/igsleo.html>). From Germany the European Space Agency (ESA), the GeoForschungsZentrum (GFZ) in Potsdam and the Forschungseinrichtung Satellitengeodäsie, Technical University of Munich (TUM), very successfully participated

in this LEO orbit comparison campaign. Much progress was achieved in orbit modeling, parameterization and data processing due to these comparisons efforts. In this context, the importance of the availability of SLR measurements to CHAMP for validation purposes cannot be stressed enough.

A second orbit comparison campaign is now under way for a selected time interval of JASON-1 data (and possibly CHAMP data, too). The JASON-1 satellite is tracked by GPS, SLR, and DORIS and allows, therefore, various orbit comparisons between techniques. One of the goals of the campaign is to study the possible impact of LEO GPS data on global IGS products like site coordinates, GPS orbits and clocks, and Earth rotation parameters. These studies should be seen in view of the fact that by 2010 20-30 LEO satellites with GPS receivers onboard might be revolving the Earth (ROTHACHER et al., 2002, 2003).

Towards Real-Time Orbit Determination

During the time interval covered by this report the determination of near real-time or even real-time orbits for various satellite missions and satellite systems has become more and more an issue. An ever increasing number of applications of the GPS, for instance, require near real-time or real-time orbits with a very high precision. Typical examples are GPS meteorology, where the wet troposphere estimates computed from GPS have to be available for weather predictions within 1-3 hours, high-accuracy real-time positioning, and real-time orbit determination of LEOs. A DORIS tracking system onboard a LEO satellite can nowadays be equipped with a real-time orbit determination software in order to compute the orbit of the spacecraft in real-time with high accuracy. Similar developments exist for GPS receivers onboard LEO satellites.

For the CHAMP mission, near-real time orbit determination and orbit prediction schemes are discussed, e.g., in (KÖNIG et al., 2000, 2002; MICHALAK et al., 2003; SCHMIDT et al., 2003). Concept studies for rapid orbit determination of LEO satellites to support future mission operations (e.g., TerraSAR-X) are also performed by the Deutschen Zentrum für Luft- und Raumfahrt (DLR).

A similar development towards real-time as for LEO orbits also takes place within the IGS. Besides rapid products for GPS satellite orbits and clocks, ultra-rapid products are now available with a delay of a few hours only, including predictions for the next 24 hours. ESA and GFZ are involved in these IGS activities (GENDT et al., 2000; FANG et al., 2001).

New Measurement Types

During the last few years the quality of the data delivered by space-borne GPS receivers has dramatically improved and GPS receivers onboard LEOs have become a very powerful tool for high-precision orbit determination, allowing an uninterrupted, continuous tracking of the satellite in its orbit. Also the DORIS system has been enhanced, changing now to second generation satellite instrumentation with improved tracking capabilities (e.g. ability to process two beacon signals at a time) and accuracy. Not only the quality of tracking data improved, but – mainly as a result of the

new satellite missions – also new measurement types became available that enable, support or complement orbit determination strategies: accelerometers, gradiometers, star sensors, K-band measurements and other inter-satellite links.

The accelerometers flying on CHAMP and GRACE now (see, e.g. (SCHWINTZER et al., 2000)), allow to measure the non-gravitational accelerations on the satellite. The data may not only be used to remove non-gravitational effects disturbing gravity field determination, but also to study the quality of orbit force models for air drag and solar radiation pressure and to improve these models. Many groups in Germany have started to use these accelerometer data in their gravity field research work and orbit determination work. Gradiometry, planned for the ESA mission GOCE, will measure the second spatial derivatives of the gravity field and add an additional new data type to study the high-order terms of the gravity field. More details and references may be found in Section II: "Satellite Gravity Field Missions".

Star sensors continuously measure the attitude of the spacecraft with respect to the stars. Exact knowledge of the attitude of a spacecraft is essential not only to determine the precise location of the onboard instruments (GPS antenna, SLR reflector, ...) in space but also for the modeling of air drag and solar radiation pressure. Star sensor measurements thus contribute important information to the orbit determination process.

First results for the GRACE satellite pair, where the distance between the two spacecrafts is measured with an accuracy of a few ten microns using a K-band link (KÖNIG et al., 2002), clearly show the enormous potential of inter-satellite tracking (in this case to detect temporal variations in the Earth's gravity field) and the concept of satellite constellations. Interesting studies concerning inter-satellite links were performed by (HAMMERSFAHR et al., 1999) and (WOLF, 2001). The first of these publications describe methods of improving the satellite state vector using new kinds of links from one satellite to other satellites or to ground stations for determination of range (or range rate) and time differences. Special emphasis is put on two-directional links and the combination of this type of links with conventional ones. In the second publication the theory of orbit determination and orbit computation for GNSS satellites (GPS, GLONASS, GALILEO) is reviewed and a new approach for precise orbit and ephemeris determination using inter-satellite links is developed. The performance of such algorithms was tested using a complex simulation software package.

Inter-satellite links will become extremely important in the future, not only because these inter-satellite measurements are not affected by tropospheric delays, but also because more and more scientific missions will make use of satellite constellations instead of single satellites, making inter-satellite links between the satellites of the constellation an interesting option.

Combination of Space-Geodetic Techniques

The simultaneous availability of various observation types for the tracking of satellites (space-geodetic techniques like SLR, GPS, and DORIS, but also of new measurement types like accelerometer data, star sensors and inter-satellite links mentioned in the previous section) immediately leads to the question of how all these measurement types can be combined in an optimal and most beneficial way, when computing the orbit of satellites (and other global parameter types). Besides fundamental stations at the ground, where different geodetic observation techniques are co-located, also satellites tracked by several techniques may be used as ties between the different space-geodetic observing techniques. Typical examples are TOPEX/Poseidon or JASON-1, where GPS, SLR, DORIS, and altimetry data contain orbit information. Comparisons between the orbits derived from different observation types give important insights into possible systematic biases of the techniques. Not only the CSTG Sub-commission on "Precise Orbit Determination for Low Earth Orbiting Satellites" of the Commission on International Coordination on Space Techniques for Geodesy and Geodynamics (CSTG) (ROTHACHER, 2000; ROTHACHER et al., 2002; <http://www.iapg.bv.tum.de/cstg/index.html>) but also the IAG Special Study Group 2.162 on "Precise Orbits Using Multiple Space Techniques" (<http://www.deos.tudelft.nl/~remko/ssg2.162>) has its research focus on these inter-technique issues.

The combination of the different space-geodetic techniques will become more and more important, because the satellite tracking data contains information on all three pillars of space geodesy, namely site coordinates and satellite orbits (geometry), Earth rotation, and the gravity field. On the long run, only a rigorously combined adjustment of all three types of parameters from the ensemble of space-geodetic observations (GPS, SLR, VLBI, DORIS, etc.) will give highly consistent and accurate results. In view of the huge amount of global parameters and the biases between techniques to be expected in such combined solutions, this is not a trivial task at all. A first step in this direction consists of the combination of GPS ground-based (stations) and space-based (LEO) data as performed by (ROTHACHER et al., 2002 and 2003; ZHU et al., 2003), where the LEO data should help, e.g., to get more accurate geocenter estimates.

Interesting combinations of LEO and ground station GPS data are also to be expected in the area of the ionosphere and troposphere (atmospheric sounding).

Combination studies are taking place in the International Laser Ranging Service (ILRS), too. The Deutsches Geodätisches Forschungsinstitut (DGFI) in Munich and GFZ in Potsdam are involved in these activities. Besides comparisons of Lageos-1 and Lageos-2 orbits for benchmarking, efforts are directed towards a combination of SLR, GPS and other techniques.

Future Activities

It is to be foreseen that more and more satellite mission (e.g. GOCE) will be equipped with a variety of instruments (accelerometers, gradiometers, star sensors, ...) contributing to satellite orbit determination and more and more missions will consist of constellations of satellites most certainly with inter-satellite links. These developments will open an entire new field of orbit determination activities and challenges. To correctly and optimally combine all these data types will be an issue for some time to come.

In the near future more and more LEO satellites will also be equipped with high-precision tracking systems like GPS or DORIS. Therefore, basically three layers will be present: (1) the tracking stations on the ground, the LEO satellites, and the Medium and/or Geostationary Earth Orbiters (MEO and GEO) like GPS, GLONASS and GALILEO. The combined analysis of the various space-geodetic data to determine not only the satellite orbits, but also site coordinates, Earth rotation parameters, and gravity field coefficients will be a challenging task. This is also one of the principle goals of the IAG project IGGOS (Integrated Global Geodetic Observing System).

The various institutions involved in orbit determination in Germany will certainly continue to play an important role in this field and in view of the interesting present and future missions (CHAMP, GRACE, JASON-1, ENVISAT, ICESAT, and GOCE), requiring high-precision orbits to fulfill their mission goals, the groups involved in these activities might even increase.

Bibliography

- BOOMKAMP, H., "The CHAMP Orbit Comparison Campaign", in *First CHAMP Mission Results for Gravity, Magnetic and Atmospheric Studies*, Springer Verlag, Reigber, C. et al, eds., 2002.
- DOW, J.M., FELTENS, J., GARCIA, C., ROMERO, I., *The ESA/ESOC IGS Analysis Centre*, Annual Report 2000, International GPS Service 2000 Technical Report, JPL Publication 02-012, IGS Central Bureau eds., Pasadena CA, Jet Propulsion Laboratory, 2001.
- FANG P., GENDT G., SPRINGER T., MANUCCI T.: *IGS Near Real-time Products and their Applications*. *GPS Solutions*, Vol. 4, No. 4, p.2-8, 2001
- GENDT G., DICK G., SOEHNE W.: *GFZ Analysis Center of IGS -- Annual Report for 2000*. IGS 2000 Technical Reports, Eds. K. Gowey, R. Neilan, A. Moore, JPL, Pasadena, CA, pp. 95-98, 2001
- GENDT G., FANG P., ZUMBERGE J.F.: *Moving IGS towards real-time*, IGS Analysis Center workshop, 8-10 June 1999, La Jolla, CA, USA, Eds. K. Gowey, R. Neilan, A. Moore, JPL/IGS Central Bureau, Pasadena, CA, pp. 391-404, 2000
- GENDT, G., CH. REIGBER, G. DICK: *Ultra Rapid GPS Orbits and its Application in Near Real-Time Water Vapor Estimation*; EOS Transactions Suppl., Vol. 81, F315, 2000
- HÄHNLE H.: *Modellierung von Satellitenoberflächen für die Berechnung von Oberflächenstörkräften am Beispiel des Satelliten CHAMP (Modelling of satellite surfaces for the computation of surface perturbations – case study CHAMP)*, study report, Geodetic Institute, University of Stuttgart, Germany, 1999
- HAMMESFAHR J., HORNPOSTEL A., HAHN J., TRAUTENBERG H., RAPP C., SPECHT W. (DLR) EISSFELLER B., WOLF R., BALBACH O., ZINK T., FU Z. (IfEN), MALTHAN H., LEMKE N. (Kayser-Threde), SOUTY P., LEVAVASSEUR D. (Dassault Electronique), SCHÄFER W. (TimeTech), TAVELLA P., LEONARDI M. (IEN): *Usage of Two-Directional Link Techniques for Determination of the Satellite State for GNSS-2*, National Technical Meeting and Joint, 19th Biennial Guidance Test Symposium, US Institute of Navigation, San Diego, CA, Jan. 25-27, 1999
- INEICHEN D., ROTHACHER M., SPRINGER T., BEUTLER G.: *Computation of Precise GLONASS Orbits for IGEX -98*, Geodesy Beyond 2000, Challenges of the First Decade, IAG General Assembly, Birmingham, July 19-30, 1999/IAG Symposia, Vol. 121, 26-31, Springer, Berlin/Heidelberg, 1999
- JOHANNSEN B.: *Berechnung des Einflusses der Erdalbedo auf eine Satellitenbahn (Influence of Earth radiation on the orbit of a satellite)*, study report, Geodetic Institute, University of Stuttgart, Germany, 1999
- KOENIG R., REIGBER CH., NEUMAYER K.H., SCHMIDT R., ZHU S.Y., BAUSTERT G., FLECHTNER F., MEIXNER H.: *Satellite Dynamics of the CHAMP and GRACE LEOs as Revealed from Space- and Ground-Based Tracking*, World Space Congress – 2002 Abstracts, The World Space Congress Houston, Texas, USA, AIAA, Abstract 01959, 10-19, 2002
- KOENIG R., NEUMAYER K.H.: *Thermospheric Events in CHAMP Precise Orbit Determination*; in Reigber/Luehr/Schwintzer (Ed.): *First CHAMP Mission Results for Gravity, Magnetic and Atmospheric Studies*, pp.112-119, Springer, 2003
- KOENIG R., K.H. NEUMAYER, G. MICHALAK, L. GRUNWALDT: *CHAMP Clock Error Characterization*; in Reigber/Luehr/Schwintzer (Ed.): *First CHAMP Mission Results for Gravity, Magnetic and Atmospheric Studies*, pp.32-37, Springer, 2003
- KOENIG R., S.Y. ZHU, CH. REIGBER, K.H. NEUMAYER, H. MEIXNER, R. GALAS, G. BAUSTERT, P. SCHWINTZER: *CHAMP Rapid Orbit Determination for Atmospheric Limb Sounding*; *Advances in Space Research* 30(2), 289-293, 2002
- KOENIG R., G. BAUSTERT, R. GALAS, H. MEIXNER, K.H. NEUMAYER, V. SCHWIEGER, S.Y. ZHU: *CHAMP Near-real-time Precise Orbit Determination*. EOS, Transactions, American Geophysical Union, Vol. 81, No.48, F315, 2000
- KRAUS S.: *Wirkung der Atmosphärenreibung auf Satelliten; Entwicklung einer Matlabfunktion*, study report, Geodetic Institute, University of Stuttgart, Germany, 1998
- MANDEL J., MÜLLER J.: *Visualisierungsmöglichkeiten in der Satellitengeodäsie mit Hilfe des Programmpaketes Satellite Tool Kit STK 4.0.3b der Firma AGI (Visualzation for satellite geodesy by means of Satellite Tool Kit (STK) 4.0x by AGI)*, study report, Geodetic Institute, University of Stuttgart, Germany, 1999
- MICHALAK G., G. BAUSTERT, R. KOENIG, CH. REIGBER: *CHAMP Rapid Science Orbit Determination – Status and Future Prospects*; in Reigber/Luehr/Schwintzer (Ed.): *First CHAMP Mission Results for Gravity, Magnetic and Atmospheric Studies*, pp.98-103, Springer, 2003
- MONTENBRUCK O., GILL E.: *Ionospheric Correction for GPS Tracking of LEO Satellites*; *The Journal of Navigation* 55, 293-304, 2002

- MONTENBRUCK O., KROES R.: In-flight Performance Analysis of the CHAMP BlackJack Receiver; submitted to: *GPS Solutions*, 2003
- MONTENBRUCK O.: *Kinematic GPS Positioning of LEO Satellites using Ionosphere-free Single Frequency Measurements; accepted for: Aerospace Science and Technology*, 2003
- NEUMAYER K.-H., ZHU S.Y., REIGBER CH., KOENIG R., MEIXNER H.: *CHAMP Orbit Recovery – Algorithmic Approaches and Results*. EOS, Transactions, American Geophysical Union, Vol.81, No.48, F 309, 2000
- NEUMAYER K.H., R. KOENIG, CH. REIGBER, S.Y. ZHU: *Approaches to CHAMP Precise Orbit Determination*; in Reigber/Luehr/Schwintzer (Ed.): First CHAMP Mission Results for Gravity, Magnetic and Atmospheric Studies, pp.78-84, Springer, 2003
- NITSCHKE N.: *SATLAB – ein Werkzeug zur Visualisierung von Satellitenbahnen*, Schriftenreihe des Instituts für Astronomische und Physikalische Geodäsie/Forschungseinrichtung Satellitengeodäsie, No. 2, München, 1999.
- PFISTER C.: *Gravitative Einflüsse anderer Himmelskörper auf Satellitenbahnen mit Umsetzung in eine Matlabfunktion (Third bodies gravitational effects on satellite orbits and implementation as a Matlab module)*, study report, Geodetic Institute, University of Stuttgart, Germany, 1999
- ROMERO, I., BOOMKAMP, H., DOW, J., GARCIA, C., *GPS Orbit Processing In Support Of Low Earth Orbiter Precise Orbit Determination*, Advances in Space Research 31(4), 2003.
- ROMERO, I., GARCIA, C., KAHLE, R., DOW, J., MARTIN-MUR, T., *Precise Orbit Determination of GLONASS Satellites at the European Space Operations Centre*, Advances in Space Research 30(2), 281-288, 2002.
- ROTHACHER M.: *Comparison of absolute and relative antenna phase center variations*, GPS Solutions, Vol. 4, 455-60, Wiley, 2001
- ROTHACHER M., G. MADER: *Receiver and Satellite Antenna Phase Center Offsets and Variations*, Position Paper of the "Antenna Session", IGS Workshop in Ottawa, 2002
- ROTHACHER M., SVEHLA D.: *Report on the Activities of the Subcommittee on Precise Orbit Determination for Low Earth Orbiting Satellites*, IAG Commission VIII – International Coordination of Space Techniques for Geodesy and Geodynamics: Progress Report 2001, 64-69, Deutsches Geodätisches Forschungsinstitut, München, 2002
- ROTHACHER M., SVEHLA D.: *Impact of GPS tracking data of LEO satellites on global GPS solutions*, The new Face of Space: 34th COSPAR Scientific Assembly, 246, American Institute of Aeronautics and Astronautics, Houston, 2002
- ROTHACHER M.; D. SVEHLA: *Impact of LEO satellites on global GPS solutions*, Geophysical Research Abstracts: EGS-AGU-EUG Joint Assembly, Vol. 5, Nice, 2003
- ROTHACHER M.: *Report on the Activities of the Subcommittee on Precise Orbit Determination for Low Earth Orbiting Satellites*, IAG Commission VIII – International Coordination of space techniques for Geodesy and Geodynamics: Status and Program 1999-2003, 62-63, Deutsches Geodätisches Forschungsinstitut, München, 2000
- SCHMIDT R.: *Numerische Integration gestörter Satellitenbahnen mit Matlab*, Schriftenreihe des Instituts für Astronomische und Physikalische Geodäsie/Forschungseinrichtung Satellitengeodäsie, No. 5, München, 1999.
- SCHMIDT R., M. ROTHACHER: *Estimation of Elevation-Dependent GPS Satellite Antenna Phase Center Variations*, Geophysical Research Abstracts: 27th EGS General Assembly, Vol. 4, Nice, 2002
- SCHMIDT R., M. ROTHACHER: *Estimation of Satellite Antenna Phase Center Variations*, IGS-Workshop 2002, Ottawa, 2002
- SCHMIDT R., BAUSTERT G., KOENIG R., REIGBER CH.: *Orbit Predictions for CHAMP – Development and Status*; in Reigber/Luehr/Schwintzer (Ed.): First CHAMP Mission Results for Gravity, Magnetic and Atmospheric Studies, pp.104-111, Springer, 2003
- SCHWINTZER P., KANG Z., PEROSANZ, F.: *Accelerometry Aboard CHAMP*. In: Rummel, Drewes, Bosch, Hornik (Eds.): Towards an Integrated Global Geodetic Observing System (IGGOS). International Association of Geodesy Symposia, Vol. 120, 197-200, 2000
- SHI CH., L. GRUNWALDT, J.-C. RAIMONDO, F.-H. MASSMANN, S.Y. ZHU: *Determination of the CHAMP GPS Antenna with Respect to Satellite's Mass Center*, in Reigber/Luehr/Schwintzer (Ed.): First CHAMP Mission Results for Gravity, Magnetic and Atmospheric Studies, pp.38-41, Springer, 2003
- SPRINGER T., BEUTLER G., ROTHACHER M.: *Improving the Orbit Estimates of the GPS Satellites*, Journal of Geodesy, Vol. 73, 3147-157, 1999
- SPRINGER T., BEUTLER G., ROTHACHER M.: *A new Solar Radiation Pressure Model for GPS*, Advances in Space Research: COSPAR Scientific Assembly, Nagoya, Japan, July 12-19, 1998, Vol. 23, 4673-676, 1999
- SVEHLA D., ROTHACHER M.: *Kinematic Orbit Determination Of LEOs Based On Zero Or Double-Difference Algorithms Using Simulated And Real SST GPS Data*, IAG 2001 Scientific Assembly: Budapest, 2001
- SVEHLA D., ROTHACHER M.: *Kinematic and Reduced-Dynamic Precise Orbit Determination of Low Earth Orbiters*, submitted to Advances in Geosciences, 2002
- SVEHLA D., ROTHACHER M.: *Comparison of kinematic and reduced-dynamic orbit determination strategies for CHAMP and JASON*, The new Face of Space: 34th COSPAR Scientific Assembly, American Institute of Aeronautics and Astronautics, Houston, 2002
- SVEHLA D., ROTHACHER M.: *Integrated kinematic and reduced-dynamic orbit determination of LEOs with ambiguity Resolution*, Geophysical Research Abstracts: 27th EGS General Assembly, Vol. 4, Nice, 2002
- SVEHLA D., ROTHACHER M.: *Kinematic and reduced-dynamic precise orbit determination of CHAMP satellite over one year using spaceborne GPS phase zero-differences only*, Geophysical Research Abstracts: EGS-AGU-EUG Joint Assembly, Vol. 5, Nice, 2003
- SVEHLA D., ROTHACHER M.: *CHAMP Double-Difference Kinematic POD with Ambiguity Resolution*, First CHAMP Mission Results for Gravity, Magnetic and Atmospheric Studies, 70-77, Springer, Berlin/Heidelberg, 2003
- WOLFR.: *Satellite Orbit and Ephemeris Determination Using Intersatellite Links*, Ph.D. Thesis, University of the Armed Forces Munich, Faculty of civil engineering, Neubiberg, 2001-03-13, <http://137.193.200.177/ediss/wolf-robert/meta.html>
- XU G.: *A concept of precise kinematic positioning and flight-state monitoring from the AGMASCO practice*; Earth, Planets and Space, Vol. 52, 831-835, 2000

ZHU S.Y., F.-H. MASSMANN, Y.Q. YU, CH. REIGBER: *Satellite antenna phase center offset and scale errors in GPS solutions*. GeoForschungsZentrum Potsdam, Scientific Technical Reports, STR01/12, p. 8-17, 2001

ZHU S.Y., K.H. NEUMAYER, F.-H. MASSMANN, CH. SHI, CH. REIGBER: *Impact of Different Data Combinations on the CHAMP Orbit Determination*; in Reigber/Luehr/Schwintzer

(Ed.): *First CHAMP Mission Results for Gravity, Magnetic and Atmospheric Studies*, pp.92-96, Springer, 2003

ZUMBERGE J., GENDT G.: *The demise of the selective availability and implications for the International GPS Service*, Physics and Chemistry of the Earth (A), Vol.26, No.6-8, pp.637-644, 2001

Satellite Altimetry

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The mapping of the ocean surface and the monitoring of its temporal variations by satellite altimetry contributes essentially to the solution of fundamental problems of physical geodesy. The mean sea level approximates the geoid, that equi-potential surface of the Earth gravity field that – by definition – should serve as a global height reference surface. Sea level variations allow to estimate ocean mass redistribution, one component of the global hydrological cycle, expected to be observed by the new dedicated gravity field missions CHAMP and GRACE. Synergies with this new missions and the upcoming, high resolution gravity field mission GOCE will allow to obtain 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 and will be used together with vertical density profiles to get a reliable estimate of heat flux and deep ocean current – processes in the system Earth with strong impact to global change. Today, satellite altimetry is a well established space technique. Only a few publications outline the general possibilities and limitations of satellite altimetry (BRAUN et al. 2000a, SCHÖNE et al. 2001a) and indicate the general impact of this space technique on physical geodesy (BOSCH et al. 2001). The majority of investigations focus on specific aspects reviewed in the following sections.

Harmonization and Data Base Developments

The need for a continuous, consistent and long-term altimeter time series is a well recognized fundamental requirement. It can only be achieved by the combination of altimeter missions, that are as far as possible harmonized, carefully calibrated and validated. Altimeter data has to be upgraded as soon as new ocean tide models are available or new orbits can be computed on the basis of improved gravity fields. The combination of missions with different sampling characteristic is necessary to improve the spatial and temporal resolution, a task in general *not* performed by those space agencies that operate individual altimeter missions. It turns out that there is a general need for an altimeter service – similar to already existing services for precise positioning techniques like GPS, laser tracking and VLBI. As a logical consequence, satellite altimetry was recognized by the Commission for the Coordination of Space Techniques for Geodesy and Geodynamics, CSTG (DREWES et al. 2000, DREWES et al. 2002a). The CSTG decided at the IUGG General Assembly, 1999 in Birmingham to initiate a Subcommittee on Multi-Mission Satellite Altimetry (<http://www.dgfi.badw.de/SCOMMSA>). The subcommittee discussed the establishment of an international altimeter

service, IAS, as a core element of a global geodetic/geo-physical observing system (BOSCH 2000). It also worked on a general concept and the requirements for a multi-mission altimeter data base, a necessary foundation to obtain a consistent, long-term altimeter time series. The altimeter processing system for ERS and Envisat, developed and operated at the German Processing and Archiving Center (D-PAC) was further developed (BRAUN et al. 2000b, RENTSCH et al. 2000) and now realizes to some extent the requirements of a multi-mission altimeter data base, called ADS Central, see <http://op.gfz-potsdam.de/ads>. An independent development (<http://www.dgfi.badw.de/OpenADB>) focusses on a modular, open data base with public, non-proprietary software, that allows fast parameter updates and user defined data base extracts. Both systems are still under development and compete with similar systems in other countries like RADS from Delft University and value-added products of AVISO. A MatLab toolbox for processing of TOPEX/Poseidon data has been developed by STEIGENBERGER (2002).

Calibration and Validation

The current altimeter mission scenario is characterized by five altimeter satellites operating simultaneously, namely ERS-2 and Envisat, TOPEX/Poseidon and Jason-1 and GFO. The situation requires a careful cross-calibration of all systems in order to achieve synergies by combining the different orbit and sampling characteristics and to continue the successful monitoring initiated by Geosat, the ten years observation period of TOPEX/Poseidon and the ERS-1/ERS-2 missions (BOSCH 2002a). Laser altimetry from the ICESat mission, launched in January 2003, and the upcoming Cryosat mission, to be launched in 2004, with a scanning altimeter mode both set up completely different requirement for the cross-calibration. The Cryosat project office <http://www.cryosat.de> at the Alfred Wegener Institut in Bremerhaven acts as a focal point not only for German investigations.

German groups contribute to the *absolute* range calibration of altimeter systems by development, deployment and operation of ruggedized GPS buoys in the North-Sea (SCHÖNE et al., 2001b, 2002) and the western Mediterranean Sea (SCHÜLER et al., 2003). The buoys are equipped with auxiliary sensors and data communication systems in order to allow instantaneous sea surface height determination in near-real time. The calibration of altimeter systems by GPS buoys and – more general – the use of GPS on floating platforms for mapping river, lake and sea levels was discussed in the

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The *relative* cross-calibration of Envisat and ERS-2 (in conjunction with TOPEX/Poseidon, Jason-1 and GFO) is under study by international expert teams. The German contribution will analyse dual-satellite crossovers on both, regional and global scale and perform comparison between altimetric sea level time series and tide gauge registrations.

Regional unification of the Geosat, TOPEX/Poseidon, ERS-1, ERS-2 and Envisat altimetry missions has been studied in the Mediterranean Sea. Dual satellite crossovers were analysed to estimate relative range biases and long-term drifts of the missions. In order to exclude sea level variability crossovers with a time difference of less than 10 days have been used. (FENOGLIO-MARC 2001b, FENOGLIO-MARC and GROTEN 2002a). For the non-contemporaneous TOPEX/Poseidon and Geosat missions, the sea level variability is taken into account using a model derived from sea surface temperature data (FENOGLIO-MARC and GROTEN 2002c). Linear relative trends are observed in the dual satellite crossover differences of ERS and TOPEX/Poseidon. They are smaller in the period 1995 – 1998 (ERS-2 and TOPEX/Poseidon), and negative from 1999 on. These trends may arise from long-term sensor drifts or errors in the geophysical correction. They can be partly explained by the ionospheric correction from the Bent model, applied to ERS-2 data. Total electronic content (TEC) estimates from GPS-based global ionospheric maps improve the data. In order to avoid that residual trends are interpreted as long-term sea level change, tide gauge data was used as external comparison. The agreement is superior with TOPEX/Poseidon than with ERS-2. Therefore ERS-2 was corrected (FENOGLIO-MARC 2002a).

LIEBSCH et al. (2002) performed an *absolute* comparison of altimetric sea surface heights of Geosat, ERS-1, ERS-2 and TOPEX/Poseidon by extrapolation of two tide gauge recordings in the southern Baltic Sea, that got a geocentric position by combining GPS observation, leveling data and regional geoid information. The calibration of ERS altimetry data is also performed through comparison with tide gauge data in the western Spitzbergen shelf (BRAUN, 1999). Another attempt to absolutely compare satellite altimetry and tide gauge registration at the coast of Venezuela is reported by ACUÑA and BOSCH (2003).

Beside the range calibration the wind speed estimate and the wave height measurement were also subject to calibration and validation activities. SCHÖNE and EICKSCHEN (2000) perform wind speed and significant wave height calibration in the North Sea, EICKSCHEN et al. (2001) try to improve the algorithm for estimating surface wind speed from altimetry, and EICKSCHEN et al. (2002) compare significant wave height estimates from altimetry and synthetic aperture radar images.

Sea Level Variability

There are a number of investigations about sea level variability at low and medium frequencies. Studies were performed on regional scale (Mediterranean Sea, Baltic Sea,

North Sea and Caribbean Sea), basin scale (North Atlantic, Pacific and Tropical Pacific) as well as on global scale.

FENOGLIO-MARC et al. (2000) and FENOGLIO-MARC (2001a) apply, for example, spectral analysis, Principal Component Analysis (PCA), and Canonical Correlation Analysis (CCA) to monitor regional sea level variability. The variability is based on single-satellite altimetry data with sea surface temperature, sea level pressure and surface wind speed taken into account by the CCA. ACUÑA et al. (2002) investigate correlations between multi-mission altimeter time series and tide gauge registrations at the coast of Venezuela. BOSCH et al. (2002a) used harmonic analysis and PCA to identify the dominant modes of sea level variability in the Caribbean Sea.

In the Mediterranean long-term sea level changes from multi-mission altimetry and tide gauge data are compared by FENOGLIO-MARC (2002a). Different rate of sea level changes are found in the western Mediterranean (almost zero) and the eastern Mediterranean (9 mm/yr). The negative rate of change (-11 mm/yr in mean), observed in the Ionian Sea, is also present in the sea surface temperature change. Since the 1990s, all monthly tide gauge data from the Permanent Service for Mean Sea Level (PSMSL) show an increase in sea level rate change (FENOGLIO-MARC and MARTINEZ-GARCIA, 2001). In the Ionian Sea tide gauge data from local organisation and altimetry data show, however, a decrease in the sea level rate change (FENOGLIO-MARC 2002c).

Sea level variability (SLV) models are constructed in the Mediterranean Sea from monthly averaged sea surface heights (SSH) using PCA and CCA analysis. The model based on CCA with sea surface temperature as predictor gives a good representation of the variability for the analysed time interval (FENOGLIO-MARC 2001a). Temperature changes explain a great part of the observed sea level changes both at annual that at interannual time scales (FENOGLIO-MARC, 2002c). The long term sea level height change due to thermal expansion, evaluated from annual temperature anomaly data of the World Ocean Atlas 1998 (WOA98) in the interval 1993-1998, in agreement with the observed long-term sea level changes. However, as in WOA98 the temperature anomalies are available only up to 500 meter depth, the observed change could not be fully explained. The SLV models are applied to correct the altimetry data for the sea level variability signal and to compute a mean sea level model (FENOGLIO-MARC and GROTEN 2002b).

The North Atlantic was subject to several investigations: ESSELBORN et al. (1999, 2001a, 2001b) use altimeter data to describe how changes of the geostrophic surface circulation are related to the North Atlantic Oscillation, NAO, and consider altimetry based estimates of heat storage in the North Atlantic for the period 1992-1998. The thesis of ESSELBORN (2001) elaborates in detail the relationship between sea surface heights and ocean circulation in the North Atlantic. BOSCH et al. (2002b), DREWES et al (2002b), KUHN et al. (2002) and KUHN et al. (2003) report about a two years project in the North Atlantic performed to identify and monitor anomalous sea level evolution by analysis of tide gauge data and an eight years batch of TOPEX/Poseidon

altimetry data. Heights and vertical velocities of the tide gauges are estimated from dedicated GPS campaigns and continuously operating GPS receivers. After removal of seasonal and other periodic effects a PCA of residual sea level anomalies identifies indeed a significant sea level change in winter 1996 coinciding with a remarkable fall of the NAO index.

For the period 1992-1999 TOPEX/Poseidon data were analysed in the Tropical Atlantic Ocean by spectral analysis, PCA, and CCA (GROTEN et al. 2000, FENOGLIO-MARC 2002b). With the CCA 10-day averages on 1.0 degree grid meshes were analysed in two sub-regions, Nino-3 and Nino-4, representing the eastern and the western part of the equatorial Pacific Ocean. The CCA was applied for the prediction of inter-annual climate fluctuations. BOSCH (2001) performed EOF-analysis of eight years sea level anomalies from TOPEX/Poseidon in the Pacific and elaborated the dominant modes of the strong El Niño and La Niña-events 1997/1998

Sea Level, Geoid and Ocean Dynamics

Of particular interest is the closure between altimetric derived sea level, the geoid and the ocean circulation as obtained by independent numerical models. The relationship can be used either to improve the geoid (which is still justified by the deficiencies of current gravity field models), or to obtain an estimate of the dynamic ocean topography, independent of ocean hydrodynamics.

In his thesis LUDWIG (1999) reviews the sea level determination from numerical solutions of the Navier-Stokes differential equations. The long-term determination of the sea surface topography is considered in BOSCH (1999). BOSCH (2002b) indicates the impact of the sea surface topography to the definition of a unique global height system. BLINKEN (1999) and BLINKEN and KOCH (2001) investigate the simultaneous improvement of both, the geoid and the sea surface topography by applying the adjoint method to assimilate altimeter data. The assimilation of altimeter data into numerical models is subject of several investigation. VOGELER and SCHRÖTER (1999) show how TOPEX/Poseidon data is fitted to a regional ocean model with adjustable boundaries. SCHRÖTER and WENZEL (2001) indicate the prospects to estimate the ocean circulation from Jason altimeter data. WENZEL and SCHRÖTER (2002) consider the assimilation of altimeter data using global ocean models and LOSCH et al. (2002) estimate a mean ocean state combining sea surface heights and hydrographic data within a non-linear inverse section models. A few investigations (HELM et al. 2001 and HELM et al. 2002) synthesise altimeter data in order to provide an instantaneous sea level for the calibration of the Shuttle X-SAR topography mission.

Altimetry, Earth Rotation and Earth Gravity Field

In the last decades altimetry has substantially improved the static modelling of the Earth gravity field. The most recent multi-mission estimates of the mean sea surface provide a nearly global resolution of 2'x2' and the altimeter time series is now long enough to study gravity field variations. There-

fore, even in the presence of dedicated gravity field missions, altimetry will remain an important source for the determination of the high resolution and time variable gravity field.

BOSCH et al. (2000) have shown that on the basis of Kaula's first-order theory dual satellite crossover data can be used to estimate correction for the harmonic coefficients of the Earth gravity field. They also estimate datum offsets (equivalent to degree one coefficients) of Geosat and ERS-1 relative to TOPEX/Poseidon. BAUMGARTNER (2001) investigates in detail the simultaneous estimation of gravity field correction and the large scale variations of sea level. Satellite Crossover data is also used by KLOKOWNIK et al. (2002) to evaluate the quality of the Pre-CHAMP gravity field models GRIM5-S1 and GRIM5-C1. GRUBER et al. (2000) estimate ocean mass redistribution from altimetry and circulation models and indicate the impact of the mass redistribution on the Earth gravity field. The ocean mass redistribution also influences the Earth rotation. JOCHMANN (2002) demonstrates that altimetry can be used to estimate ocean angular momentum functions. KUHN (2002) considers the mean rate of sea level change for the period 1992-2000, subtracts an estimate of the steric effect and computes the corresponding geoid changes.

References

- ACUÑA, G., W. BOSCH (2003): *Absolute comparison of satellite altimetry and tide gauge registration in Venezuela*. In: Hwang, H. et al. (Eds.) IAG Symposia, Springer, Berlin (im Druck)
- ACUÑA, G., W. BOSCH, B. MEISEL (2002): *Correlation between multi-mission altimeter time series and tide gauge registrations in the Caribbean Sea*. Proceedings of the IAG Symposium on Vertical Reference Systems, Cartagena, Colombia, IAG Symposia, Vol. 124, 231-237, Springer
- BAUMGARTNER, M. (2001) *Simultane Schätzung von Schwerefeldkorrekturen und großskaligen Meeresspiegelschwankungen aus Satellitenaltimeterdaten*. Deutsche Geodätische Kommission, Reihe C, Heft 545, München
- BLINKEN, R. (1999) *Bestimmung von Geoid und Meerestopographie aus Altimeterdaten mittels der Adjungierten Methode*. Shaker, Aachen
- BLINKEN, R., KOCH, K. R. (2001): *Geoid and sea surface topography derived from ERS-1 altimeter data by the adjoint method*. *Studia geoph. et geod.* 45, 235-250
- BOSCH, W. (1999): *Langzeitbestimmung der absoluten dynamischen Topographie*. In: WOCE Abschlußbericht des Alfred-Wegener-Institut für Polar- und Meeresforschung, 208-218, Bremerhaven.
- BOSCH, W. (2000): *CSTG Subcommission on Multi-Mission Satellite Altimetry (ScomMSA)*. IAG CSTG Bulletin No. 16, 59-61, Munich
- BOSCH, W. (2001): *EOF-Analysen der Meeresspiegelschwankungen im Pazifik*. *Zeitschrift für Vermessungswesen*, Jahrgang 126, Heft 2, S. 74-81
- BOSCH, W. (2002a): *Multi-Mission Satellite Altimetry Continuing*. IAG CSTG Bulletin No. 17, Munich, p. 60-63
- BOSCH, W. (2002b): *The Sea Surface Topography and its Impact to Global Height System Definition*. Proceedings of the

- IAG Symposium on Vertical Reference Systems, Cartagena, Colombia, IAG Symposia, Vol. 124, 225-230, Springer
- BOSCH, W., J. KLOKOCNIK, C. WAGNER, J. KOSTELECKÍ (2000): *Geosat and ERS-1 datum offsets relative to Topex/Poseidon estimated simultaneously with geopotential corrections from multi-satellite crossover altimetry*. In: Rummel, R., H. Drewes, W. Bosch, H. Hornik (Eds.): *Towards an Integrated Global Geodetic Observing System (IGGOS)*. IAG Symposia (120) 96-98, Springer, Berlin.
- BOSCH, W., M. KUHN, M. BAUMGARTNER, R. KANIUTH (2001): *Überwachung des Meeresspiegels durch Satellitenaltimetrie – Ergebnisse und Folgerungen für die Geodäsie*. Zeitschrift für Vermessungswesen, Jahrgang 126, Heft 5, S. 262-269
- BOSCH, W., G. ACUÑA, R. KANIUTH (2002a): *Caribbean Sea Level Variability from TOPEX/Poseidon Altimetry*. Proceedings of the IAG Symposium on Vertical Reference Systems, Cartagena, Colombia, IAG Symposia, Vol. 124, 249-254, Springer
- BOSCH, W., H. DREWES, P. HÄFELE, K. KANIUTH, R. KANIUTH, M. KUHN, K. STUBER, H. TREMEL (2002b): *The EVAMARIA Project: Identification and verification of sea level anomalies in the North Atlantic*. Proceedings of the IAG Symposium on Vertical Reference Systems, Cartagena, Colombia, IAG Symposia, Vol. 124, 238-243, Springer
- BRAUN A. (1999): *Calibration of ERS altimetry data through tide gauge data in the western Spitsbergen shelf*. Scientific field report LSF Ny-Alesund, grant NMA-99/2-1
- BRAUN, A., A. HELM, CH. REIGBER, M. RENTSCH, T. SCHÖNE (2000a): *Altimetrie und Meeresspiegel*, Zweijahresbericht 1998/1999, GeoForschungsZentrum Potsdam (GFZ), p. 13-27,
- BRAUN, A., S. EICKSCHEN, A. HELM, M. RENTSCH, T. SCHÖNE (2000b): *The ENVISAT RA-2 Value-Added Ocean/Ice Processor at GFZ Potsdam*. ESA - ERS/ENVISAT Symposium, Gothenburg, Sweden
- DREWES, H., W. BOSCH, H. HORNIK (Eds.) (2000): *Commission VIII – International Coordination of Space Techniques for Geodesy and Geodynamics (CSTG), Status and Program 1999-2003*. IAG CSTG Bulletin No. 16, Munich
- DREWES, H., W. BOSCH, H. HORNIK (Eds.) (2002a): *Commission VIII – International Coordination of Space Techniques for Geodesy and Geodynamics (CSTG), Progress Report 2001*. IAG CSTG Bulletin No. 17, Munich
- DREWES, H., W. BOSCH, K. KANIUTH (2002b): *Erkennung und Verfolgung anomaler Meerwasserstände mit Altimetrie und Pegelregistrierungen im Nord-Atlantik*. Deutsches Geodätisches Forschungsinstitut, München
- EICKSCHEN, S., T. SCHOENE, A. BRAUN, A. HELM (2001): *Steps towards an Improved Algorithm for Ocean Near Surface Wind Speeds derived from Satellite Radar Altimeter Data*. Eos Trans. AGU, 82(47), Fall Meet. Suppl., Abstract OS51C-0495.
- EICKSCHEN, S., D. HOJA, S. LEHNER, T. SCHOENE (2002): *Comparison of Radar Altimeter and SAR-Imagette Derived Significant Wave Height*. Eos Trans. AGU, 83(47), Fall Meet. Suppl., Abstract OS72A-0340.
- ESSELBORN, S. (2001): *Meereshöhen und ozeanische Zirkulation im Nordatlantik zwischen 1992 und 1998 - Eine Radaraltimeter-Studie*. Dissertation, Fachbereich Geowissenschaften, Univ. Hamburg, 143 pp.
- ESSELBORN, S., R. CHENEY, L. MILLER (1999): *Changes of the Geostrophic Surface Circulation in the North Atlantic Related to the North Atlantic Oscillation as measured by Satellite Altimetry*. IEEE Proc. IGARSS'99, 2007-2009.
- ESSELBORN, S., C. EDEN (2001): *Sea Surface Height changes in the North Atlantic Ocean Related to the North Atlantic Oscillation*. Geophys. Res. Letters, 28, 3473-3476.
- ESSELBORN, S., L. MILLER, R. CHENEY (2001): *Heat Storage in the North Atlantic Ocean between 1992 and 1998 as estimated by satellite altimetry*. GKSS-report 2001/31, 76-80.
- FENOGLIO-MARC L. (2001a): *Analysis and representation of regional sea level variability from altimetry and atmospheric data*. Geophysical Journal International, Vol. 145, Issue 1, pp. 1-18
- FENOGLIO-MARC L. (2001b): *Multi-mission altimetry data analysis and unification in the Mediterranean Sea*. ERS-ENVISAT Symposium Proceedings, ESA SP-461, (CD-Rom)
- FENOGLIO-MARC L. (2002a): *Long-term sea level change in the Mediterranean Sea from multi-satellite altimetry and tide gauge stations*. Physics and Chemistry of the Earth, Vol. 27, pp. 1419-1431
- FENOGLIO-MARC L. (2002b): *Sea level variability in Tropical Pacific 1992-1999*. TUD/IPG/Alt Internal Report N.2
- FENOGLIO-MARC L. (2002c): *Long-term sea level change in the Ionian Sea*. TUD/IPG/Alt Internal Report N.3
- FENOGLIO-MARC L., Y. WANG, E. GROTEN (2000): *Investigation at regional scales of sea level variability at low and medium frequencies*. AVISO Newsletter N.7, pp.40-43 CNES
- FENOGLIO-MARC L., M. MARTINEZ-GARCIA (2001): *Sea level trends in the Mediterranean Sea from satellite altimetry and tide gauge stations*. Proceedings of Final Workshop of Cost Action 40. Sea level in Europe: Observation, Interpretation and Exploitation, pp. 114-117, Hydrographic Institute of the Republic of Croatia, Split
- FENOGLIO-MARC L., E. GROTEN (2002a): *Modelling the sea level variation for the unification of altimetric missions*. Adv. Space Res., Vol. 30/11, pp. 2357-2362
- FENOGLIO-MARC L., E. GROTEN (2002b): *Local improvement of the marine geoid using altimetry data submitted to "Cahiers of EGS"*. Proceedings of Workshop on Analytical Representation of Potential Field Anomalies for Europe
- FENOGLIO-MARC L., E. GROTEN (2002c): *On the variability of mean sea level*. Allgemeine Vermessung Nachrichten AVN 2/2003, Wichmann, pp. 55-59
- GROTEN E., FENOGLIO L., WANG L. (2000): *El Nino 1997 – main characteristics and interannual earth rotation variability*. Allgemeine Vermessungs-Nachrichten 4/2000, Wichmann, pp. 140-146
- GRUBER, TH., CH. REIGBER, J. WÜNSCH (2000): *Estimation of ocean mass redistribution by means of altimetry and circulation models and its impact on the gravity field*. In: Rummel, R.; Drewes, H.; Bosch, W.; Hornik, H. (Eds.), *Towards an Integrated Global Geodetic Observing System (IGGOS)*, International Association of Geodesy Symposia, 120, Springer-Verlag, Berlin, 218-221
- HELM, A., A. BRAUN, M. RENTSCH, T. SCHOENE (2001): *Calibration of X-SAR During the Shuttle Radar Topography Mission Using Synthetic Altimeter Data*. Eos Trans. AGU, 80(46), Fall Meet. Suppl., Abstract G22A-08.
- HELM, A., A. BRAUN, S. EICKSCHEN, T. SCHÖNE (2002): *Calibration of the Shuttle Radar Topography Mission X-SAR Instrument Using a Synthetic Altimetry Data Model*.

- Canadian Journal of Remote Sensing, Volume 28, Number 4, 573-580
- JOCHMANN, H. (2002): *Die ozeanische Erregerfunktion, abgeleitet aus Altimeterdaten*. In: Schuh, H.; Soffel, M.; Hornik, H. (Ed.), Vorträge beim 4. DFG-Rundgespräch im Rahmen des "Forschungsvorhabens Rotation der Erde" zum Thema "Wechselwirkungen im System Erde", Höllenstein/Wetzell, 8.-9. März 2001, Deutsche Geodätische Kommission, Reihe A, 118, Beck, München, 125-127
- KUHN, M. (2002): *Geoid variations due to mean sea-level variations*. In: Drewes, H., Dodson, A.H., Fortes, L.P.S., Sanchez, L., Sandoval, P. (eds) Vertical Reference Systems, IAG Symposia 124: 238-243, Springer Berlin.
- KUHN, M., W. BOSCH, R. KANIUTH (2002): *Sea level variations in the North Atlantic*: In: Adam, J., K.-P. Schwarz (Eds.): Vistas for Geodesy in the New Millennium. IAG Symposia, Vol. 125, 487-492, Springer
- KUHN, M., BOSCH, W., KANIUTH, R. (2003): *Low frequency variations and anomalous behaviour of the North Atlantic sea level measured by TOPEX/Poseidon altimetry*. Submitted to Marine Geodesy.
- KLOKOWNIK, J., REIGBER, CH. SCHWINTZER, P., WAGNER, C.A., KOSTELECKÝ, J. (2002): *Evaluation of Pre-CHAMP Gravity Models 'GRIM5-S1' and 'GRIM5-C1' with Satellite Crossover Altimetry*. Journal of Geodesy 76, 189-198.
- LIEBSCH, G., K. NOVOTNY, R. DIETRICH, C.K. SHUM (2002): *Comparison of Multimission Altimetric Sea Surface Heights with Tide Gauge Observations in the Southern Baltic Sea*. Marine Geodesy, 25, 213-234
- LUDWIG, J. (1999) *Höhenbestimmung aus ozeanischen Strömungsmodellen*. Shaker, Aachen
- RENTSCH, M., A. BRAUN, A. HELM, T. SCHÖNE (2000): *Operational Altimetry at GFZ - From ERS-2 to Envisat*. ESA - ERS/ENVISAT Symposium, Gothenburg, Sweden
- SCHÖNE, T., S. EICKSCHEN (2000): *Wind Speed and SWH Calibration for Radar Altimetry in the North Sea*. ESA - ERS/ENVISAT Symposium, Gothenburg, Sweden.
- SCHÖNE, T., A. BRAUN, C. REIGBER (2001a): *Altimetrie und Meeresspiegel - Möglichkeiten und Grenzen der Beobachtung*. Zürich, GAIA 10 (2001) 3, 226-229
- SCHÖNE, T., A. BRAUN, CH. REIGBER (2001b): *Kontinuierliche Überwachung von Pegelstationen und GPS Hochseebojen*. Deutscher Hydrographentag 2001, Potsdam.
- SCHÖNE, T., M. FORBERG, R. GALAS, C. REIGBER (2002): *GPS-buoys for lifetime RA drift monitoring*. AGU Fall Meeting 2002, EOS Trans. AGU, 83(47), Fall Meet. Suppl., Abstract OS52A-0189.
- SCHUELER, T., B. ZIMMERMANN, G. W. HEIN (2003): *Radar Altimeter Calibration of the Envisat Satellite: An Autonomous System of High-Precision for Instantaneous Sea Surface Height Determination*. Proceedings of NTM 2003 National Technical Meeting, 22-24. January 2003, Anaheim, CA, USA
- STEIGENBERGER, P. (2002): *MATLAB-Toolbox zur TOPEX/Poseidon Altimeterdatenverarbeitung*. IAPG/FESG No.14, Institut für Astronomische und Physikalische Geodäsie, Technische Universität München
- LOSCH, M., REDLER, R., SCHRÖTER, J. (2002): *Estimating a Mean Ocean State from Hydrography and Sea-Surface Height Data with a Non-linear Inverse Section Model, Twin Experiments with a Synthetic Data Set*. Journal of Physical Oceanography, 32, 2096-2112.
- SCHRÖTER J., WENZEL, M. (2001): *Ocean circulation determined from JASON satellite altimeter data*. AVISO Newsletter, 8, 121-122
- VOGELER, A, SCHRÖTER, J. (1999): *Fitting a regional ocean model with adjustable open boundaries to TOPEX/POSEIDON data*. Journal of Geophysical Research, 104, 20789-20799.
- WENZEL, M. SCHRÖTER, J. (2002): *Assimilation of TOPEX/Poseidon data in a global ocean model*, Differences in 1995-1996, Physics and Chemistry of the Earth.

Additional bibliography made available after completion of the reports to Section II

- ANGERMANN D., THALLER D., ROTHACHER M.: *Issues of a Rigorous Combination*, Part 3: SINEX Combination Campaign, IERS Workshop on Combination Research and Global Geophysical Fluids, Munich, 2002
- BEUTLER G., BOCK H., BROCKMANN E., DACH R., FRIDEZ P., GURTNER W., HUGENTOBLER U., INEICHEN D., JOHNSON J., MEINDL M., MERVART L., ROTHACHER M., SCHAER S., SPRINGER T., WEBER R.: *Bernese GPS Software Version 4.2*, Astronomical Institute University of Berne, Bern, 2001
- BEUTLER G., ROTHACHER M., SCHAER S., SPRINGER T.A., KOUBA J., NEILAN R. E.: *The International GPS Service (IGS): An Interdisciplinary Service in Support of Earth Sciences*, Advances in Space Research, Vol. 23, 4631-653, 1999
- FANG P., GENDT G., SPRINGER T., MANUCCI T.: *IGS Near Real-time Products and their Applications*. GPS Solutions, Vol.4, No.4, p.2-8, 2001
- GENDT G., FANG P., ZUMBERGE J.F.: *Moving IGS towards real-time*, IGS Analysis Center workshop, 8-10 June 1999, La Jolla, CA, USA, Eds. K. Gowey, R. Neilan, A. Moore, JPL/IGS Central Bureau, Pasadena, CA, pp. 391-404, 2000
- GENDT G., DICK G., SOEHNE W.: *GFZ Analysis Center of IGS -- Annual Report for 2000*. IGS 2000 Technical Reports, Eds. K. Gowey, R. Neilan, A. Moore, JPL, Pasadena, CA, pp. 95-98, 2001
- GENDT G., REIGBER CH., DICK G.: *Ultra Rapid GPS Orbits and its Application in Near Real-Time Water Vapor Estimation; EOS Transactions Suppl.*, Vol. 81, F315, 2000
- GRUBER TH., REIGBER CH., SCHWINTZER P.: *The 1999 GFZ Pre-CHAMP high resolution gravity model; IAG Symposia*, in Rummel et.al. (Eds.) Geodesy beyond 2000; Springer Verlag, Heidelberg, 121, 89-95, 2000
- HABRICH H., GURTNER W., ROTHACHER M.: *Processing of GLONASS and combined GLONASS/GPS observations*, Advances in Space Research, Vol. 23, 4655-658, 1999
- HUGENTOBLER U., SPRINGER T., SCHAER S., BEUTLER G., BOCK H., DACH R., INEICHEN D., MERVART L., ROTHACHER M., WILD U., WIGET A., BROCKMANN E., WEBER G., HABRICH H., BOUCHER C.: *CODE IGS Analysis Center Technical Report 1999*, IGS 1999 Technical Reports, 59-69, IGS Central Bureau, Pasadena, 2000
- INEICHEN D., ROTHACHER M., SPRINGER T., BEUTLER G.: *Results of CODE as an Analysis Center of the IGEX-98 Campaign*, Proceedings of the International GLONASS Experiment (IGEX-98) Workshop, September 13-14, 1999, Nashville, Tennessee, USA, 157-168, IGS Central Bureau, JPL, Pasadena, California, 1999
- LUEHR H., GRUNWALDT L., FOERSTE CH., SCHWINTZER P., REIGBER CH.: *CHAMP Reference Systems, Standards and Transformations; GFZ Potsdam, CH-GFZ-RS-002, 2.0*, Technical Document, 2001
- REIGBER CH., BALMINO G., SCHWINTZER P., BIANCALE R., BODE A., LEMOINE J.-M., KOENIG R., LOYER S., NEUMAYER K.H., MARTY J.-CH., BARTHELMES F., PEROSANZ F., ZHU S. Y.: *New Global Gravity Field Models from Selected CHAMP Data Sets*; in Reigber/Luehr/Schwintzer (Ed.): *First CHAMP Mission Results for Gravity, Magnetic and Atmospheric Studies*, pp.120-127, Springer, 2003
- ROTHACHER M., BEUTLER G.: *Advanced Aspects of Satellite Positioning*, Lecture Notes of Course 699.80 at the University of Calgary, Calgary, 2002
- ROTHACHER M., ZEBHAUSER B.: *Einführung in GPS*, 3. SAPOS-Symposium, 2000
- ROTHACHER M., DILL R., THALLER D.: *IERS Analysis Coordinator*, IERS Annual Report 2001, 13-17, Verlag des Bundesamtes für Kartographie und Geodäsie, Frankfurt am Main, 2002
- ROTHACHER M., SPRINGER T., BEUTLER G., DACH R., HUGENTOBLER U., INEICHEN D., SCHAER S., WILD U., WIGET A., BOUCHER C., REINHART E., HABRICH H.: *Annual Report 1998 of the CODE Analysis Center of the IGS*, 1998 Technical Report of International GPS Service, November 61-73, IGS Central Bureau, JPL, Pasadena, CA, 1999
- ROTHACHER M., HUGENTOBLER U., SPRINGER T., SCHAER S., BEUTLER G., BOCK H., DACH R., INEICHEN D., MERVART L.: *Code IGS Analysis Center Technical Report 1999*, IGS 1999 Technical Reports, 59-69, Pasadena, 1999
- ROTHACHER M., THALLER D., DILL R.: *IERS Combination Research Centres: Forschungseinrichtung Satellitengeodäsie*, Technical University of Munich (FESG), IERS Annual Report 2001, 91-92, Verlag des Bundesamtes für Kartographie und Geodäsie, Frankfurt am Main, 2002
- ROTHACHER M.: *Combination of Space-Geodetic Techniques*, International VLBI Service for Geodesy and Astronomy: General Meeting Proceedings 2002, 33-43, National Aeronautics and Space Administration, Washington, 2002
- ROTHACHER M.: *Standards des International GPS Service (IGS)*, GPS-Antennenworkshop 200, k.A., Hannover, 2000
- ROTHACHER M.: *Towards a Rigorous Combination of Space Geodetic Techniques*, IERS Workshop on Combination Research and Global Geophysical Fluids, Munich, 2002
- SCHREIBER U., M. SCHNEIDER: *Is There A Next Generation SLR-Technology?*, Adv. Space Res., Vol. 30, No. 2, 157-161, 2002
- SCHWINTZER P., KANG Z., PEROSANZ F.: *Accelerometry Aboard CHAMP*. In: Rummel, Drewes, Bosch, Hornik (Eds.): *Towards an Integrated Global Geodetic Observing System (IGGOS)*. International Association of Geodesy Symposia, Vol. 120, 197-200, 2000
- SCHWINTZER P., REIGBER CH., BARTHELMES F., BODE A., GRUBER TH., KOENIG R., BIANCALE R., BALMINO G., LEMOINE J.-M., LOYER S., PEROSANZ F.: *Gravity Field Recovery from CHAMP: First Results*; EOS Transactions of the AGU Fall Meeting, San Francisco, USA, Suppl., 2000, Vol.81, F307, 2000
- SEITZ, F., MEYER, U. SCHREIBER, N. BRANDL F.: *A Biaxial Rayleigh- and Raman-LIDAR System for Application in Atmospheric Sounding and SLR*, Proc. SPIE, Vol. 4546, 66-73, 2002
- THALLER D., ROTHACHER M.: *Comparison and Combination of Solution Series of the Space geodetic Techniques covering one Year of Data*, Geophysical Research Abstracts: EGS-AGU-EUG Joint Assembly, Vol. 5, Nice, 2003
- THALLER D., ROTHACHER M.: *GPS and VLBI antenna behaviour derived from a GPS antenna on the Wettzell radio-telescope*, Geophysical Research Abstracts: 27th EGS General Assembly, Vol. 4, Nice, 2002

WEBER R., C. BRUYNINX, SCHERNECK H. G., ROTHACHER M.,
ANDERSEN P. H., BAKER R. F., DAM T. VAN: *GPS/
GLONASS of the IAG/ETC Working Group 6*, Marees
Terrestres. Bulletin d'Informations, Vol. 134, Royal
Belgium Observatory, 2001

WEBER R., BRUYNINX C., SCHERNECK H. G., ROTHACHER M.,
ANDERSON PH., BAKER T. F., DAM T. VAN: *Tidal effects
in GPS/GLONASS data processing*, JRS 2001: Influence
of geophysics, time and space reference frames on Earth
rotation studies, 35, Royal Observatory of Belgium,
Brussels, 2001

SECTION III

DETERMINATION OF THE GRAVITY FIELD

Determination of the Gravity Field

– Overview and highlights –

G. BOEDECKER¹

This overview is based on some 260 publications on various aspects of the gravity field produced since 1999 with contributions of German authors from geodetic and some geophysical institutions and collected for the subsequent special reports. The number of papers is much the same as for the preceding period prepared in 1999. Nevertheless, speaking of numbers we have to be aware that some of the publications are collections of individual contributions which fact not always has been taken into account, and that the statistical basis tapped is not exactly identical; insofar, quantitative statements can be approximate only. The papers are authored by about 80 residents in Germany and about the same number from outside, demonstrating the strong international cooperation. It is also remarkable, that seven names only contribute to fifty percent of the publications. No general judgement is possible on the recycling rate of contents: in some cases the creation of ideas and results is overwhelmingly high; in other cases short papers appear in different journals under slightly variable titles.

The current state of the art of gravimetry is also published in textbooks and extended overviews: W. TORGE's book 'Geodesy' appeared as 2nd edition in German and Greek and as 3rd edition in English; 'Gravimetry' appeared also in Russian. S. HEITZ prepared a second edition of his report on gravity meters and gradiometers ('Gravimeter und Gradiometer'), M. SCHNEIDER prepared a report on the methodology of gravitational field determination with satellites ('Zur Methodik der Gravitationsfeldbestimmung mit Erdsatelliten'). W. FREEDEN published a book on 'Multiscale Modelling of Spaceborne Data'.

If we try to infer from the topics of publications on the current trends of the science of the terrestrial gravity field, the following statements are suggested:

- The scientific interest in *observation techniques* was clearly dominated by *spaceborne methods*:
 - One hundred of the publications are dealing with various aspects of the recent geodetic satellite missions: more than fifty with CHAMP, launched 2000, and GRACE, flying since 2002, and a handful with GOCE scheduled for 2006. Immediate observation types are satellite-to-satellite ranges and gravity gradients. Many simulations and fundamental treatments demonstrated the gain for global gravity field and the complementary character of the missions.
 - Classical satellite (e.g. laser) tracking was continued and complemented by GPS-tracking.

- Satellite altimetry was further advanced e.g. by multi-satellite crossovers.
- *Airborne gravimetry* will fill in higher spatial resolution not accessible to spaceborne methods. Observed aircraft (total) acceleration data and GNSS-derived inertial accelerations result in vector or scalar gravity values. Large data sets were collected with scalar platform instruments. Advanced concepts such as strapdown/vector instruments are tested.
- *Classical terrestrial observation techniques* such as with relative and absolute instruments are discussed in special aspects like absolute meter intercomparisons and details of evaluation, high precision networks for regional reference and for local gravity changes monitoring and the direct and indirect effects of atmospheric variations on gravity observations. Astronomic deflections of the vertical, e.g. from CCD-zenith cameras, torsion balance observations and GPS/levelling integration are also being used. Bulk data acquisition has been carried out primarily with relative meters for interpretation, see below.
- *Modelling* the gravity field is based on the physics of potential field and on mathematics for representation. The aim is to find a set of numbers and rules (algorithm) to represent the continuous gravity field, usually approximating discrete observations of various functionals.
- Fundamental *gravity potential field problems* are a continuous matter of discussion. The boundary value problem was discussed in connection with geoid computation from airborne gravimetry; upward and downward continuation was studied. Also, Helmert's second method of condensation, an ellipsoidal Bruns formula, a minimum distance Somigliana-Pizzetti minimum distance telluroid mapping and a new normal gravity formula were published.
- The toolbox to *map* the elementary observations to a global or regional model representation includes the energy integral or the differential equation of motions integral employing time-wise or space-wise techniques numerically or (semi-) analytically.
- For *gravity potential field representation*, the classical spherical harmonics with frequency localizing property are well suited particularly for global models with even observation data coverage. In case of uneven coverage, space localising kernel functions can better accommodate the data with finer or coarser (multi-) grids. Multiscale

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methods enable space-time analyses. Specific focus was on wavelet applications. Also, point mass models, geostatistical methods and Fourier series are being used. STRAKHOV proposes the SNAP model for regional and global application.

- The enormous information gain for the global gravity field from the new satellite missions enable higher resolution models and hence requires *advanced algorithms* including the need for *regularization*.
- Many *global gravity models* including GRIMs are based on various combinations of data sets from the observation methods listed above and demonstrate significant improvements in low and higher degrees up to 360; ultra-high degree models up to $l=1800$ are useful for local and regional investigations. Some models include low order spherical harmonics for gravity changes with time. Models also permitted to compute gradients for the validation of GOCE observations.

A new World Geodetic Datum 2000 was proposed by GRAFAREND & ARDALAN using the fundamental parameters W_0 , GM , J_2 , S and their variation with time.
- *Regional gravity models* presented as geoids were computed around Japan, for Northern Germany, East Germany, Baden-Württemberg as tests for various approaches. The existing European geoid EGG97 has been improved.
- *Error analyses* such as the impact of datum inconsistencies supplement the geoid computations.
- Special models are required to describe variable Earth rotation and *tidal effects*.
- *Interpretation* may be understood as the attempt to the (geo-) physical reality from the models or immediately from gravity observations by solving the inverse problem, i.e. to infer on gravitating masses and their geometric distribution.
- Some global gravity field models also included *isostatic/topographic* coefficients. The Earths tensor of inertia is extracted.
- Extended terrestrial observation campaigns were carried out in Germany and abroad, e.g. with relative land gravimeters, marine gravimeters or airborne gravimeters, respectively, in South America, Jordan, South Africa, Skagerak, Atlantic and in the European Alps. They offered the basis for *structural geophysical investigations* such as salt dome or maar identification, valley sediment fillings with ground water deposits determination, density structures, crustal structure including rift and plate margin modelling; these studies also covered areas like Egypt, Red Sea, North Atlantic, Arctica and Antarctica etc.
- *Changes of the gravity field with time* were studied at different scales: At various volcanoes in Philippines, Colombia and Indonesia, microgravity networks were observed to infer on gravity changes caused by volcanic activities. Ice load changes cause geoid changes which were studied using viscoelastic Earth models. A network in an earthquake area in China was observed with absolute and relative meters. For global changes, parameters were included in global gravity field models, changes of W_0 were studied. Ocean currents are also a source of gravity field changes.
- The geoid is a particularly useful representation of the gravity field in that it is the geometric level surface close to the sea surface. The *sea surface topography* has been studied in relation to atmospheric changes and geoid changes. High precision geoid on land areas plays a key role for GNSS height determination. Height reference system problems are discussed.
- The interpretation of gravity field observables is facilitated if known sources of gravitation are taken into account beforehand by forward modelling. For this purpose, *digital terrain models* (DTM) are compiled e.g. by using the space shuttle SRTM (Shuttle Radar Topography Mission) data. Advancing algorithms for computing the terrain effect are a rewarding subject even after several decades of research. Also, e.g. atmospheric masses are taken into account.
- *Combination with other parameters* or observables such as seismic data further restricts the solution of inverse modelling.

Terrestrial and airborne gravimetry

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Gravity reference networks:

BEK contributes through the adjustment to a joint project for a 'Unified European Gravity Network 2002' (UEGN2002) that will provide a unification of the absolute and relative gravity reference network observations in some 25 European countries. This is a major step forward compared to the preceding UEGN94 because of the increase of countries and the incorporation of the UNIGRACE absolute gravity observations carried out in the (former) East European countries (BOEDECKER ET AL. 2002b). The experience from several gravity reference network projects demonstrates the increasing role of absolute observations and leads to the conclusion that instead of 'old' general purpose gravity reference network it is necessary to establish reference station sets dedicated to specific tasks such as ground truth for satellite gravity missions or referencing airborne gravity missions etc. (BOEDECKER 2002).

Airborne gravimetry:

In the framework of developing strapdown airborne gravimetry methodology and prototype hardware, BEK has studied the kinematic airborne GPS-positioning. It is found from test flights that regional ionospheric delay variations cause positioning error variations of up to 0.5 m in a frequency band very dangerous for the kinematic accelerations derived for high resolution airborne gravimetry. Exploiting reference network stations information, the positioning error may be reduced to a few centimetres and the kinematic acceleration errors accordingly (BOEDECKER ET AL. 2002a). The SAGS (Strapdown Airborne Gravimetry System) sensor for 3D total acceleration is an assembly of 3 (to 4) high resolution accelerometers and angular rate sensors backed by multi-antennae GPS attitude receiver (BOEDECKER 2001).

M. BECKER, Universität der Bundeswehr München:

The sixth Intercomparison of Absolute Gravimeters ICAG 2001 was conducted in July 2001, (VITUSHKIN et al, 2002a). In a close cooperation with the Bureau des Poids et Mesures in Paris-Sevres the Institute of Geodesy, University of the Bundeswehr Munich, organized the relative gravimeter observations. For the first time in these comparisons a combined adjustment of absolute and relative gravimeter observations

was enabled. Results are published in (VITUSHKINE et al., 2002b, and BECKER et al., 2003)

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(1) Gravity Data Acquisition

General

Four field campaigns have been carried out during the 1999 – 2002 working period of the SFB 267 (Collaborative Center 267 entitled "Deformation processes in the Central Andes", supported by Deutsche Forschungsgemeinschaft, Bonn, Freie and Technische Universität Berlin and GFZ Potsdam): two in Northern Chile and Southern Bolivia and one along the SALT-traverse which combines the active continental margin of the Pacific Ocean and the passive continental margin of the Atlantic. SALT stands for "South American Lithosphere Transect". Our partners in Chile, Bolivia and Argentina are organized in the MIGRA group (Mediciones Internacionales de Gravedad in los Andes).

Station spacing amounts to approximately 5 km along all passable tracks aside from some local areas with a higher station density. Extreme road conditions did not always allow us to determine the drift of the gravity meters by repeating the measurements at each station. However, even if we used bad tracks by car, the drift of the three LaCoste & Romberg instruments (models G) rarely exceeded $0.05 \cdot 10^{-5} \text{ m/s}^2$ per day.

The basis of the calculation of gravity anomalies are the two following equations:

$$BA = FA + *g_{\text{Bou}} \text{ (station complete) Bouguer anomaly}$$

$$FA = g_{\text{abs}} - (g_{\text{h}} + *g_{\text{top}} + *g_{\text{Niv}}) \text{ (station complete) Free-air anomaly}$$

with:

g_{abs} : absolute gravity at station, tied to the IGSN71 datum,

g_{h} : normal gravity at station level h; normal gravity formula of 1967,

$*g_{\text{top}}$: terrain correction,

$*g_{\text{Niv}}$: free air correction, and

$*g_{\text{bou}}$: (spherical) Bouguer slab correction.

For topographic corrections, a true 3D-method including calculations of the Earth's curvature has been applied. The corrections were calculated within a radius of 167 km; correction densities of $2\,670 \text{ kg/m}^3$ and $1\,640 \text{ kg/m}^3$ for areas

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above and below sea level, were used respectively. Typical values for the topographic correction in the Southern Altiplano vary between $0.4 H 10^{-5} \text{ m/s}^2$ (flat areas) and $1.2 H 10^{-5} \text{ m/s}^2$ (in the Cordillera de Lipez and the recent volcanic arc of the Western Cordillera). Along the southern SALT traverse ($38/-42^\circ \text{ S}$; $72 /-62^\circ \text{ W}$) topographic corrections were necessary only for stations which lay in the Andean region of the traverse.

Observations of station elevations

For safety reasons we measured with both differential GPS and barometers due to sudden cuts of electrical current which could cause the power supply of the permanent GPS station at the base camps in Uyuni (e.g. Bolivia, MIGRA 1999 campaign) and General Roccas (Argentina, MIGRA 2000 campaign) respectively. To improve the quality of our barometric measurements, we calculated time-dependent drift corrections as it is usually done for gravity measurements, using as many benchmarks and repeated measurements as possible. Moreover, the profiles of several days were tied together in order to eliminate systematic errors. The barometer scales have been calibrated on leveling lines ($H = 2000 \text{ m}$) and error estimations showed that even in the worst case the accuracy was better than 20 m , giving an error in the Bouguer anomaly of about $2 H 10^{-5} \text{ m/s}^2$, which is less than 1% of the overall magnitude of more than $450 H 10^{-5} \text{ m/s}^2$ (in the north).

Altiplano field campaigns MIGRA 1999 and 2002

The new gravity data base which is now available in the remote regions of western and southwestern Bolivia covers the high Western Cordillera, the Cordillera de Lipez, and the Southern Altiplano. The gravity field was observed in a campaign which was actively supported by the Servicio Nacional de Geología y Minería, La Paz. Gravity measurements were planned and conducted closely to members of the SFB 267 for a joint interpretation of tectonics in the southern Altiplano, in particular along the Kenyani – Lineament. The interpretation sheds light not only on local tectonics but on the structure of huge volcanic caldera complexes in the Lipez area along the Bolivian – Argentinean – Chilean border.

The Central Cordillera of the Andes is characterized by its enormous topography and remoteness, its extreme climatic conditions, low population density and limited infrastructure. Other difficulties limiting our field work were the lack of modern topographic maps and geodetic networks in the region. The investigated area belongs to the intra mountainous Altiplano-Puna Plateau with an average height of 4300 m .

Repeated measurements were carried out at 77 stations with a mean error of $0.18 10^{-5} \text{ m/s}^2$, in the worst case we observed $0.94 10^{-5} \text{ m/s}^2$. To give an impression of the received accuracies, two examples are presented here:

Length of loop (1): 593 km

Observations between:	Difference (10^{-5} m/s^2)	gravity-meter
Uyuni – Colcha K	+ 9.37	411
Colcha K – Laguna Colorada	-103.76	592
Laguna Colorada – Soniquera	71,24	592
Soniquera – Uyuni	+ 22.98	998

resulting error in loop (1): $-0.17 * 10^{-5} \text{ m/s}^2$

Length of loop (2): 512 km

Observations between:	Difference (10^{-5} m/s^2)	gravity-meter
Uyuni – Laguna Colorada	-94.51	592
Laguna Colorada – Uyuni	94.53	592

resulting error in loop (2): $+0.02 * 10^{-5} \text{ m/s}^2$

With the exception of some inaccessible regions in the southeast of the Bolivian Altiplano the obtained coverage of the entire region is fairly uniform. All measurements are tied to the IGSN71 gravity datum at base stations in Oran/Argentina, Tucumán/Argentina and Calama (Chile) via our own observational points at the Bolivian borders with Argentina (La Quiaca – Villazon) and Chile (Ollagüe – Avaroa). A rather small error of only $1.17 H 10^{-5} \text{ m/s}^2$ were obtained. At 40 reference stations we observed an average error of $0.28 H 10^{-5} \text{ m/s}^2$.

The MIGRA 1999 and 2002 gravity campaigns complete the data base in the Central Andes. Based on an earlier contract between the former Bolivian State Oil Company (YPFB) and the gravity research group at FU Berlin in this particular southern Altiplano region 10 000 gravity stations were reprocessed, tied to the IGSN71 gravity datum and connected to the gravity network of the MIGRA group and the Universidad de Chile (airport Calama, N. Chile).

Gravity observations along the SALT traverse (MIGRA 2000 campaign)

Recently (2000 and 2002) more than 2000 new gravity data were observed along the SALT (South American Lithosphere Transect) and tied to the IGSN 71 (IGM base station, Neuquen) and to IGSN stations in Chile (Temuco, Puerto Montt and the new TIGO station in Concepción). The campaign was supported by Repsol-YPF based at Neuquén and the research groups at the Universidad de Buenos Aires and Concepción. Together with the reprocessed older 50 000 gravity data in the province of Neuquen and Rio Negro which were released to us under a contract with YPF. All data were reprocessed and we calculated for more than 55.000 gravity sites "station complete" Bouguer anomalies.

At present (January/February 2003) we are engaged in a precise error analysis, data re-check of industry data which were released by several Chilean institutions for the western part of the transect. In close cooperation with these institutions (eg. Geological Surveys of Chile and Argentina, Universidad de Chile, research project of Volkswagenstiftung Hannover and oil industry (ENAP, Empresa Nacional del Petróleo) these activities will result in the compilation of

a homogeneous gravity database of the southern-central zone of Chile and central-west zone of Argentina (38/– 42° S) by reprocessed existing gravity data and observed new data sets.

Station	Gravity (mGal)	Latitude	Longitude	Height (m)	Location
47612J	980282.26	41° 25.9' S	73° 05' W	81	BM Field El Tepual

In total there are some 80.000 gravity measurements (at the continent) available which are supplemented by free-air gravity (SANDWELL and SMITH data set or KMS, Copenhagen/Denmark altimeter data) in the offshore area of the Pacific and Atlantic Oceans. The gravity research group participated in the German research vessel SONNE cruise (SO 141 1 & 4) to observe new ship borne gravity data together with the colleagues from BGR (Hannover, Germany and GEOMAR, Kiel, Germany)

Field campaign in the Jordan (DESERT 2002)

Under the umbrella of the DESERT project (Dead Sea Rift Transect) some 800 new stations were observed in the Dead Sea Valley (Jordan) together and with the logistical assistance of the Jordan Geological Survey. The 2002 field measurements will be interpreted in an interdisciplinary model which will shed light on the complicated structure of the Dead Sea Transform. The project brings scientists from Germany, Israel, Jordan and Palestine together and is financed by the Deutsche Forschungsgemeinschaft (DFG, Bonn, Germany).

Participation in the international TRANSALP project

Recently the Eastern Alps were subject to seismic research which was conducted in the context of the German, Austrian and Italian TRANSALP project. Our 3D modelling of the density structure belonged to a series of piggy-back projects which were closely accomplished to the seismic reflexion studies. We conducted a combined gravity-seismic interpretation which based on the results of both older deep seismic profiling, and the new TRANSALP profile. Special emphasize was put on geology and tectonic information which served as model constraints for near-surface structures. 3D forward modelling (by Dr. J. EBBING, PhD thesis) of both the Bouguer gravity field and geoidal undulations provides in-depth insight into the lithosphere and considers the constraining conditions. Due to the uncertainties of used constraints, particularly in depths of the Eastern Alpine Moho, an inversion technique complemented this study and provided insight into the shape and density contrast at the crust-mantle interface. Partners in this project were Dr. C. BRAITENBERG (University of Trieste, Italy and Prof. Dr. B. MEURERS, Vienna University, Austria and the TRANSALP Research Group).

(2) Software for data processing and interpretation

For processing purposes we used self written computer software (DbGrav, JAVA) which stores reference numbers, coordinates and heights for each new gravity station and calculates tidal corrections, terrain corrections on the base of the 1 km H 1 km digital elevation grid released by the

ENAP (8 000 stations),

US National Imagery Agency (NIMA) (180 stations) and Moreno Project (1996) (283 stations). All the measurements are linked to IGSN 71 gravity datum via the base station at Puerto Montt:

USGS. Drift corrections of both, gravity and barometric readings and the final station complete Bouguer- and free-air anomalies and even isostatic residual fields were calculated immediately. A plot program contoured the new anomaly maps immediately after new data were processed. Therefore, we always were able to check and test the new field data across the old data base and recognize inconsistencies immediately.

For 3D forward modelling of geoidal undulations, gravity and its derivatives the software IGMAS (interactive gravity and magnetic application system) was completed and expanded by a visualization package (http://userpage.fu-berlin.de/~sschmidt/Sabine_IGMAS.html).

U. F. MEYER, GeoForschungsZentrum Potsdam

The project CHICAGO (Chilean Coastal Aero-Geophysical Observations) was initiated and performed by the GFZ Potsdam, Section 1.3 "Gravitational Field und Earth Models". The project and survey was supported in finances and personnel by the SFB-267, herein especially by the FU Berlin. The BEK Munich contributed to the project with its strap-down gravity meter system. Project partners on the Chilean side were the Instituto Geografico Militar (IGM) and the Fuerza Area de Chile, Servicio Aerofotogrametrico (SAF). The observation platform of the aerogravimetry system was a Twin Otter of the SAF which was normally used only for photogrammetry.

The project CHICAGO is closely connected to ongoing and future scientific investigations in Chile, that are performed by the GFZ Potsdam and partner institutions. Herein, especially the SFB-267 "Deformation Processes in the Andes" and the planned TIPTEQ project "From The Incoming Plate to Mega-Thrust Earthquakes" are the main links of CHICAGO.

The aero-profiles of the CHICAGO survey area in 2002 concentrated in the area between 37 and 39 degrees south. The line spacing offshore was 12 km. In total, 20 east-west trending profiles were flown in a flight altitude of 300 meters above water. Onshore, 8 north-south profiles were flown with a line spacing of 10 to 20 kilometers, here the flight altitudes varied between 2000 and 2700 meters depending on topography. One of the core issues of the project was to chart the changing character of the subduction zone around 40 degrees south. Along the central Andean mountain belt a deep oceanic trench, a narrow shelf and high plateaus dominate. South of 40 degrees south, the depth of the trench decreases, the shelf gets broader and the mountain fade out. Moreover, at about 40 degrees south only weak gravimetric

anomalies are observed along the coast. North and south of it, strong positive Bouguer anomalies strike along the coastline. In 2002 the northern part of this structural change was mapped by means of aerogravity. In 2003 or 2004 the southern part is planned to flown to map the full extend of the geologic and tectonic pattern.

G. JENTZSCH, Institute für Geowissenschaften der Universität Jena, Lehrstuhl für Angewandte Geophysik

Micro-gravimetry at volcanoes – measurements and interpretation:

Since 1992 we carry out repeated micro-gravity measurements at different volcanoes. Up to now we have completed the work at Mayon Volcano / Philippines, whereas the data of Merapi Volcano / Indonesia is still under consideration. The work at Galeras Volcano / Colombia had to be stopped due to the political situation; but we hope that due to improvements we will be able to resume the measurements soon. Our interpretation of the gravity differences observed concentrates on the derivation of internal processes under the boundary conditions of elevation changes (determined by GPS) and findings from geology and geochemistry, e.g. the composition and viscosity of the volcanoes.

Numerical interpretation of gravity data:

Starting in 1990 our group has a good record of research projects regarding the evaluation of the gravity field with respect to underground structure of the geology and the tectonic development. Recent works emphasized on the Main Ethiopian Rift, the Vogtland / NW-Bohemia area famous for its swarm earthquakes, and the Red Sea Rift / Egypt. Our concern is to combine the geological structure derived from the gravity field modelling with dynamic modelling of the tectonic development of the area under study.

Marine gravimetry:

During the voyages of the polar research vessel "Polarstern" a marine gravimeter of the type KSS31 – 1725 (Bodenseewerk Überlingen) is in operation. I summer 1998, Gerhard Jentzsch participated the expedition ARK XIV/1a from Bremerhaven to the Alpha Ridge close to the North Pole until Tixi / Russia. During this trip he was responsible for the marine gravimeter, to keep it running and to check the settings.

J. MÜLLER, IfE, Uni Hannover

In ANDERSEN et al. (1999), several aspects are discussed how the formulas and quantities given in the sections 'The solid Earth pole tide effect on the geopotential' and 'The site displacement caused by rotational deformation due to polar motion' of the IERS Conventions (1996) should be applied.

MÜLLER et al. (2002) give an overview which tidal models are used worldwide in the various computer programs for the analysis of Lunar Laser Ranging (LLR) data and which tidal parameters are determined by LLR, e.g. the lunar tidal

acceleration or Love numbers of the Moon. MÜLLER and TESMER (2002) continue these investigations and discuss also how well terrestrial Love numbers (h_2 , l_2) or amplitudes of typical diurnal and semi-diurnal periods can be derived from LLR data.

Literature

BOEDECKER, BEK, München

BOEDECKER G.: *World gravity standards – present status and future challenges*. Metrologia 2002, 39 no.5, 429-434

BOEDECKER G.; V. BÖDER; C. VÖLKSEN; G. WANNINGER W. WENDE: *Precise GPS-Positioning and Acceleration for Airborne Gravimetry: A Case Study*. Proc., IGGC Meeting Thessaloniki 2002a

BOEDECKER G.; A. KENYERES; O. FRANCIS: *Unified European Gravity Reference Network 2002 (UEGN2002): A Status Report*. Proc., IGGC Meeting Thessaloniki 2002b

BOEDECKER G.: *Sensor Calibration and Orientation for Strap-Down Airborne Gravimetry by GPS*. Paper, IAG Gen.Ass. Budapest 2001

M. BECKER Uni BW München:

VITUSHKIN L., M. BECKER, Z. JIANG, O. FRANCIS, T. M. V. DAM, J. FALLER, J.-M. CHARTIER, M. AMALVICT, S. BONVALOT, N. DEBEGLIA, S. DESOGUS, M. DIAMENT, F. DUPONT, R. FALK, G. GABALDA, C. G. L. GAGNON, T. GATTACCECA, A. GERMAK, J. HINDERER, O. JAMET, G. JEFFRIES, R. KÄKER, A. KOPAEV, J. LIARD, A. LINDAU, L. LONGUEVERGNE, B. LUCK, E. N. MADERAL, J. MÄKINEN, B. MEURERS, S. MIZUSHIMA, J. MRLINA, D. NEWELL, C. ORIGLIA, E. R. PUJOL, A. REINHOLD, PH. RICHARD, I. A. ROBINSON, D. RUESS, S. THIES, M. VAN CAMP, M. VAN RUYMBEKE, M. F. DE VILLALTA COMPAGNI, S. WILLIAMS (2002a): *Results of the Sixth International Comparison of Absolute Gravimeters ICAG-2001*, Metrologia, Vol 39(5), in press.

VITUSHKIN L., Z. JIANG, M. BECKER, O. FRANCIS (2002b): *Analysis of the Results of the Sixth International Comparison of Absolute Gravimeters ICAG-2001*, Proc. 3rd Meeting Int. Gravity and Geoid Commission, August 20.-23, 2002, Thessaloniki, Greece, pp 1-6.

BECKER M., ZHIHENG JIANG, L. VITUSHKIN (2003): *Adjustment of Gravity Measurements at the Sixth International Comparison of Absolute Gravimeters ICAG-2001*, Proc. Instrumentation and Metrology in Gravimetry IMG-2002, Institut d'Europe, Münsbach Castel, Luxembourg, 28, 29 and 30 October 2002, Cahiers of ECGS, Luxembourg, in press.

H.-J. GÖTZE, FU Berlin

2000:

BRAITENBERG C., H.-J. GÖTZE, T. JAHR, G. JENTZSCH, S. SCHMIDT, G. STRYKOWSKI, (Editors) 2000: *Potential fields in geodesy, geophysics and geology. Inversion and interpretation of gravity and magnetic anomalies on all scales, case histories*. Physics and Chemistry of the Earth, pp. 343-393.

CHOIS.-CH., 2000: *Horizontale und vertikale Dichtezonierung in den Varisziden am Beispiel des Erzgebirges Dissertation FB Geowissenschaften, FU Berlin, Berliner Geowissenschaftliche Abhandlungen, Reihe B, Bd. 38, p. 105.*

GIESE P., G. ASCH, H. BRASSE, H.-J. GÖTZE, R. KIND, P. WIGGER, M. ARANEDA, E. KAUSEL, E. MARTÍNEZ, J. VIRAMONTE, 2000: *Structures and processes in the Central Andes*

revealed by geophysical investigations. *Zeitschrift für Angew. Geologie*, Sonderheft 1, pp. 303-309.

KRAWCZYK C.M., STEIN, E., CHOI, S., OETTINGER, G., SCHUSTER, K., GÖTZE, H.-J., HAAK, V., ONCKEN, O., PRODEHL, C., SCHULZE, A., 2000: *Geophysical constraints on exhumation mechanisms of high-pressure rocks: the Saxo-Thuringian case between Franconian Line and Elbe Zone*. In Special Publication of the Geological Society of London 179, "Orogenic Processes – Quantification and Modelling in the Variscan Belt of Central Europe". Eds: Franke, Oncken, Tanner. Geological Society, London, pp. 303-322.

2001:

EBBING J., GÖTZE, H.-J. (2001). *Preliminary 3D density modeling along the TRANSALP-profile*. Österreichische Beiträge zu Meteorologie und Geophysik, Wien, H 26, ISSN: 1016-6254, pp. 125-136.

EBBING J., BRAITENBERG C., GÖTZE H.-J., MEURERS B., 2001. *The Density Structure of the Eastern Alpine Crust*. 5th Workshop of Alpine Geological Studies, Obergurgl (Austria). Geologisch-Paläontologische Mitteilungen Innsbruck, 73, 2001. Abstract.

EBBING J., C. BRAITENBERG, H.-J. GÖTZE, 2001: *Forward and inverse modeling of gravity revealing insight into crustal structures of the Eastern Alps*. *Tectonophysics*, 337, pp. 191-209.

GÖTZE H.-J., BRAITENBERG C., EBBING J., 2001. *Isostasy, Lithospheric Loads and Flexural Rigidity in Collisional Orogens Constrained by 3D Modeling of Geoid and Gravity Field*. Talk at IUGG/IASPEI 2001 General Assembly, Hanoi (Vietnam).

GOLTZ G., 2001: *Lokale Schwerefeldbestimmung und -modellierung mit Hilfe der Ableitungen des Schwerepotentials*. Dissertation, FU Berlin, Berliner Geowissenschaftliche Abhandlungen, Reihe B, Bd. 39, pp 135.

LI X., H.-J. GÖTZE, 2001: *Ellipsoid, geoid, gravity, geodesy and geophysics – a tutorial*. *Geophysics*, vol. 66, no. 6, pp. 1660-1668.

OMARINI R., H.-J. GÖTZE, R.J. SUREDA, A. SEILACHER, F. PFLÜGER, 2001: *Puncoviscana folded belt in NW Argentina: testimony of Late Proterozoic Rodinia fragmentation and pre-Gondwana collisional episodes: a reply*. *International Journal of Earth Sciences (Geol. Rundschau)*, Vol. 90, pp. 894-902.

2002:

BRAITENBERG C., J. EBBING, H.-J. GÖTZE, 2002: *Inverse modeling of Elastic thickness by convolution method – the Eastern Alps as a case example*"; *Earth and Planetary Science Letters*, 202, 387-404.

EBBING J., 2002: *3-D Dichteverteilung und isostatisches Verhalten der Lithosphäre in den Ostalpen*. Dissertation, FB Geowissenschaften, FU Berlin. <http://www.diss.fu-berlin.de/2002/192/>

GÖTZE H.-J., S. KRAUSE 2002: *The Central Andean Gravity High, arelic of an old subduction complex?* *Journal of South American Earth Sciences*, 14 (8), pp.799-811.

GÖTZE H.-J., S. SCHMIDT, 2002: *Geophysical 3D Modeling using GIS-Functions*. In "8th annual conference of the international association for mathematical geology", ISSN: 0946-8978, Terra Nostra, Heft 04/2002, pp. 87-92

KUDER J., 2002: *3D Schwerefeldmodellierungen zur Erfassung des tiefen Untergrundes im Nordost-Deutschen Becken*. Dissertation FR Geophysik, Fachbereich Geowissenschaften, pp. 116. (<http://www.diss.fu-berlin.de/2002/139/>).

OTT N., H.-J. GÖTZE, S. SCHMIDT, H. BURGER, M. ALTEN, 2002: *Meta Geo-information System Facilitates Use of Complex Data for Study of Central Andes*. *EOS*, Vol. 83, No. 34. http://www.agu.org/eos_elec/020081e.html.

WITTKOPF V., 2002: *Analyse und Formalisierung geophysikalisch-geologischen Wissens am Beispiel der integrierten Interpretation krustaler Strukturen*. Dissertation, FU Berlin, Berliner Geowissenschaftliche Abhandlungen, Reihe B, Bd. 40, p. 107.

G. JENTZSCH, University Jena

JENTZSCH G., M. CALVACHE, A. BERMUDEZ, M. ORDOÑEZ, 1999. *Microgravity and GPS at Galeras Volcano, Colombia: Establishment of a new network and first measurements*. Extended Abstracts, Int. Symp. on Andean Geodynamics, Göttingen, Oktober 1999, 377 – 380.

JENTZSCH G., M. CALVACHE, A. BERMUDEZ, M. ORDOÑEZ, A. WEISE, G. MONCAYO, 2000. *Microgravity and GPS at Galeras Volcano / Columbia: The new network and first results*. *Deutsche Geophys. Ges., Sonderband IV /2000* (Herausg.: B. Buttkus, S. Greinwald, J. Ostwald), 49-52.

GERSTENECKER C., G. JENTZSCH, G. LÄUFER, B. SNITIL, I. SUYANTO, A. WEISE, 2000. *Repetition network and digital elevation models at Mount Merapi, Indonesia*. *Cahiers du Centre Européen de Géodynamique et de Séismologie*, 17, 201-205.

JENTZSCH G., 2000. *Symposium JSV36 "Understanding Volcanoes by Geodesy, Seismology, Electromagnetics and Geochemistry"*. In: Torge (Hrg.), *Berichte zur XXII. Generalversammlung der IUGG Assoziation für Geodäsie – Birmingham, Juli 1999*. *Zeitschr. für Vermessungswesen*, Heft 7/2000, p. 233.

GERSTENECKER C., G. JENTZSCH, G. LÄUFER, A. SETIAWAN, B. SNITIL, A. WEISE, 2000. *Schwere- und Höhenänderungen am Merapi, Indonesien – Messung, Ergebnisse und der Versuch einer Interpretation*. In: *Fachrichtung Bauingenieurwesen und Geodäsie der TU Darmstadt, Festschrift anlässlich der Vollendung des 65. Lebensjahres von Prof. Dr. Ing. Bernhard Wrobel*. Schriftenreihe Fachrichtung Geodäsie, 89 – 101.

FERNANDEZ J., CHARCO M., TIAMPO K.F., JENTZSCH G., RUNDLE J.B., 2001. *Joint interpretation of displacement and gravity data in volcanic areas*. A test example: Long valley caldera, California. *Geophys. Res. Lett.*, 28/6, 1063–1066.

FERNANDEZ J., TIAMPO K.F., JENTZSCH G., CHARCO M., RUNDLE J.B., 2001. *Inflation or deflation? New results for Mayon volcano applying elastic-gravitational modeling*. *Geophys. Res. Lett.* Vol. 28/12, 2349 – 2352.

JENTZSCH G., R.S. PUNONGBAYAN, U. SCHREIBER, G. SEEBER, C. VÖLKSEN, A. WEISE, 2001. *Mayon volcano, Philippines: Change of monitoring strategy after microgravity and GPS measurements*. *J. Volcanol. Geotherm. Res.*, 109/1-3, 219-234.

MAHATSENTE R., G. JENTZSCH, T. Jahr, 1999. *Crustal structure of the Main Ethiopian Rift from gravity data: 3-dimensional modeling*. *Tectonophysics* 313, 363 – 382.

JENTZSCH G., R. MAHATSENTE, T. JAHR, 2000. *Three dimensional inversion of gravity data from the Main Ethiopian Rift*. *Phys. Chem. Earth (A)*, Vol. 25, No. 4, 365 – 373.

- MAHATSENTE R., G. JENTZSCH, T. JAHR, 2000. *Three dimensional inversion of gravity data from the Main Ethiopian Rift*. J. African Earth Scs., Vol. 31, No. 2.
- HOFMANN Y., T. JAHR, G. JENTZSCH, P. BANKWITZ, K. BRAM, 2000. *The gravity field of the Vogtland and NW Bohemia: Presentation of a project*. Studia Geophysica et Geodaetica, 44/4, 608 – 610.
- HOFMANN Y., T. JAHR, G. JENTZSCH: *Gravimetric modelling and studies of the gravity field of the Vogtland area and its surroundings*. J. Geodyn., in press.
- KURZ J., T. JAHR, G. JENTZSCH, 2002. *Geodynamic modelling of the recent stress and strain field in the Vogtland swarm earthquake area using the finite-element method*. J. Geodyn., in press.
- KURZ J., T. JAHR, G. JENTZSCH, 2002. *Pore pressure induced stress accumulation and the connection to pore pressure diffusion in swarm earthquake areas.*, Tectonophysics, in press.
- MOSTAFA S. S. M., T. JAHR, G. JENTZSCH, A. S. M. MOSTAFA, N. M. ABOU ASHOUR, 200?. *Crustal evaluation of the northern Red Sea Rift, Egypt from geophysical data: 3-dimensional modeling*. J. African Earth Scs. (submitted)
- WEIGELT E., G. JENTZSCH, K. SCHÜLER, 1999. *Gravimetry*, in: W. Jokat (ed.), ARCTIC '98: The Expedition ARK XIV/1a of RV "Polarstern" in 1998, Bremerhaven – Tiksi, Berichte zur Polarforschung, 308, '99, AWI, Bremerhaven, p. 25-29.
- J. MÜLLER, IfE, Univerity Hannover**
- ANDERSEN P.H., SCHUH, H., MÜLLER, J.: *Explanatory Supplement to the Sections on 'The solid Earth pole tide effect on the geopotential' and 'The site displacement caused by rotational deformation due to polar motion' of the IERS Conventions (1996)*. In: Explanatory Supplement to the IERS Conventions (1996) Chapters 6 and 7, DGFI Report No. 71, P. 13-18, ed. by H.Schuh, 1999.
- MÜLLER J., TESMER V.: *Investigation of Tidal Effects in Lunar Laser Ranging*. Journal of Geodesy, Vol. 76, P. 232-237, 2002.
- MÜLLER J., CHAPRONT J., RIES J.G., WILLIAMS J.: *LLR and Tidal Effects*. Bulletin D'Informations Marees Terrestres (BIM), ed. by B.Ducarme, Vol. 134, P. 10553-10557, 2002.
- Additional literature from Bundesamt für Kartographie und Geodäsie, Außenstelle Leipzig**
- Gravimetry**
- TORGE W., SCHNUELL M., TIMMEN L., JIA M., XING C., LI H.: *Absolute and relative gravimetry 1990 / 1992 / 1995 in the Western Yunnan Earthquake Prediction Experimental Area*. Deutsche Geodätische Kommission, Reihe B, 307, München 1999. 48 S.
- HECK B., GROTEN E., RUMMEL R., HORNIK H. (Red.) *National report of the Federal Republic of Germany on the geodetic activities in the years 1995-1999: XXII General Assembly of the International Union for Geodasy and Geophysics (IUGG) 1999 in Birmingham, (Landesbericht der BRD ueber die geodätischen Aktivitäten in den Jahren 1995-1999: XXII. Generalversammlung der IUGG 1999 in Birmingham)*, Deutsche Geodätische Kommission, Reihe B; 308, Muenchen, 1999. – 124 S.
- MEYER U. F.: *Untersuchung struktureller Elemente des südöstlichen Weddellmeeres / Antarktis auf der Basis mariner Potentialfelddaten*, in: Berichte zur Polarforschung; 323, (Die Arbeit ist die inhaltlich unveränderte Fassung einer Dissertation, die 1995 dem Fachber. Geowiss. der Uni. Bremen vorgelegt wurde.) Bremerhaven, 1999. – 173 S.,
- LEHMAN R. *Boundary-value problems in the complex world of geodatic measurements* in: Randwertprobleme in der komplexen Welt der geodätischen Messungen, J. geod., Berlin Vol. 73, Nr. 9, Oktober 1999. – p. 491-500
- HEITZ S.: *Grundlagen der physikalischen Geodäsie: Ergänzungen zur 3. Auflage*. Kapitel 5, in: Mitteilungen aus dem aus den Geodätischen Instituten der Rheinischen Friedrich-Wilhelms-Universität Bonn; 85, Bonn, 1999. – 533 S.
- LEHMANN R. *Altimetry-gravimetry problems with free vertical datum*, in: Altimetrie-Gravimetrie-Probleme mit dem freien Höhendatum J. geod., Berlin Vol. 74, Nr. 3-4 = Mai 2000. – p. 327-334
- GROTEN E.: *Modelle und Modellierung in der Geodäsie*, (Festschrift anlässlich der Vollendung des 65. Lebensjahres von Prof. Dr. Ing. BERNHARD P. WROBEL), Schr. Reihe Fachr. Geod. Techn. Univ. Darmstadt, Darmstadt, 2000, H. 10. – p. 109-116
- ILK K.-H.: *Bericht über die Geodätische Woche GW 2001 in Köln vom 18.-21. September 2001*, Z. Geod., Geoinf. Landmanag., Augsburg 127 (2002) 2. – p. 124-128
- Terrestrial and Airborne Gravimetry**
- DOROBANTU R., ZEBHAUSER B.: *Field Evaluation of a Low-Cost Strapdown IMU by means GPS*. Ortung und Navigation 1, 51-65, DGON, Bonn, 1999
- DOROBANTU R.: *Gravitationsdrehwage*, Schriftenreihe des Instituts für Astronomische und Physikalische Geodäsie/ Forschungseinrichtung Satellitengeodäsie No. 4, 1-44, München, 1999
- DOROBANTU R.: *Simulation des Verhaltens einer lowcost Strapdown-IMU unter Laborbedingungen*, Schriftenreihe des Instituts für Astronomische und Physikalische Geodäsie/ Forschungseinrichtung Satellitengeodäsie, No. 1-17, München 1999
- MÜLLER J., OBERNDORFER H.: *Simulation of the Gradiometer Mission GOCE Artificial Satellites*, Vol. 34, No. 1, p.41-45, 1999

Global Gravity Field Modelling

T. GRUBER¹

Introduction

During the last four years the global gravity field modelling work in Germany was mainly driven by the preparation for the satellite missions CHAMP, GRACE and GOCE. Several general studies and reports for the individual missions and for mission intercomparisons were performed during this period (BALMINO et al, 1999a, 1999b; ILK, 2000; REIGBER et al, 1999b, 2000, 2002b; RUMMEL and REIGBER, 1999; RUMMEL, 2000, 2003; RUMMEL et al, 2002; SCHÄFER, 2001; SCHÄFER and GRAFAREND, 2002; TAPLEY and REIGBER, 1999; VISSER et al, 2002). In summary the result of these reports was, that all three missions have their own justification and that they provide a unique opportunity to dramatically improve our knowledge of the system Earth.

Because CHAMP was launched as the first satellite in July 2000, most of the gravity field work concentrated on this mission. Several studies investigated the potential of the mission and the performance of the instruments (OBERNDORFER et al, 2002a; SCHWINTZER et al, 2000). Results of data analysis show, that CHAMP provides a unique data set for improvement of the gravity field. In March 2002 the GRACE satellites were launched. Because the data processing system is still in the commissioning phase no real GRACE data were available for analysis. The major milestone for the GOCE mission was the approval of the mission in 1999. Since then a lot of effort went into the simulation of gradiometer data and development of processing algorithms. It is planned that GOCE will be launched in spring 2006. This means, that we will have a unique sequence of missions, which are complementary in many aspects (e.g. sequence of launch, measurements system, orbit).

Global modelling techniques

From the mathematical point of view one can distinguish global modelling technique based on the classical approach using spherical harmonics as mathematical base functions and newer developments using multiscale modelling techniques. From a geodetic point of view, apart the well known direct approach based on classical orbit perturbation theory, which was used for all actual gravity field models, new techniques for setting up the observation equations and estimation of the gravity field parameters were developed in context of the preparation of the data analysis for the new satellite missions (SCHNEIDER, 2002).

Geodetic Techniques

CHAMP and GRACE provide satellite-to-satellite range observations in the high-low or low-low mode, while GOCE will observe gravity gradients directly from space. This implies different analysis methods. On the one hand the gradiometer observes directly the gravity field at a specific time for a specific place. The instrument provides the second derivatives of the gravity potential in their different combinations, which then can be further analysed in a time-wise or space-wise sense (see later). On the other hand satellite-to-satellite tracking data are always indirect observations of gravity field perturbations, which are reflected in the relative motion between two satellites. During the orbit determination process these observations are translated into satellite positions and velocities either by a dynamic, reduced dynamic or kinematic approach (the later one does not provide satellite velocities). Now these perturbed orbit positions can be differentiated numerically to get satellite velocities (1st derivative) or satellite accelerations (2nd derivative). (For dynamic and reduced dynamic precise orbit determination the velocities are integral part of the estimation scheme and must not be derived by differentiation). The different observation types enable different analysis techniques. While positions require the solution of the differential equation of motion (numerical or semi-analytical) (SCHWINTZER, 2000, SCHWINTZER and REIGBER, 2002a), velocities can be used for solving the energy integral, which relates potential and kinetic energy (GERLACH et al, 2003a, 2003b; ILK, 2002, 2003; SNEEUW et al, 2003; VISSER et al, 2003), and accelerations together with velocities can be used for computation of the gravity gradients along the orbit (AUSTEN and REUBELT, 2000; AUSTEN et al 2002; HESS and KELLER, 1999). The later two are mathematically much more easier, because no numerical integration of the equation of motion and the variational equations has to be done.

For the analysis of the observations we can distinguish between so-called time-wise techniques, which analyse the data along the orbit in terms of orbit elements, and space-wise techniques, which express the observables in spherical (ellipsoidal) coordinates. The classical direct approach by integrating the equation of motion numerically can also be regarded, in a more general sense, as time-wise method, because the tracking data are analysed along the orbit. In this sense analytical (CUI and LELGEMANN, 2000; STRAKHOV et al, 2000) and semi-analytical approaches introducing analytical orbit theory (KAULA, HILL) and FFT methods for integration are regarded as time-wise methods (SNEEUW, 2000, 2002). Time-wise methods also play a prominent role

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for analysing future GOCE gradiometer observations (KLEES et al, 2000). In this case the integration can be avoided, because one directly observes the gravity field. On the other hand, also space-wise methods could become important for analysis of gradiometer data (ILK et al, 2002). In a similar way surface and altimeter data are handled for combined gravity field models (GRUBER, 2000). For the combination of the different data types the altimetry-gravimetry boundary-value-problem plays an additional role. A new numerical solution approach was investigated by LEHMANN and KLEES, (1999) and LEHMANN, (2000).

Several of the above data analysis methods produce large normal equation systems, which can not be solved easily. With GRACE and especially GOCE the problem will become much more dramatic, because gravity field models up to much higher degrees will be computed. Apart from the classical least squares solution methods (GRUBER, 2001a), iterative solution techniques based on conjugate gradients and other methods were developed (SCHUH, 2003). For this, regularisation techniques were applied to improve the performance of the algorithms (KOCH and KUSCHE, 2002; KUSCHE and KLEES, 2001b, 2002b, 2002c; KUSCHE, 2002b). These algorithms already show now, that the GOCE gravity field (e.g. up to degree 300) can be solved with reasonable effort.

Mathematical Techniques

As mentioned above, all classical and newly developed methods are aiming in the determination of spherical harmonic series representing the Earth's gravity potential. This implies, because one is working in the frequency domain, that theoretically global data sets have to be used to derive the series. Quasi global data sets are available from the CHAMP and GRACE missions and they are therefore perfectly suited for this purpose. For GOCE the situation will be slightly different. Due to the sun-synchronous orbit, there will be polar data gaps with an opening angle of about 6.5 degrees. Similar, surface data sets (gravity anomalies, altimeter data) to be used for combined gravity field models, have significant areas with either bad data or no data at all. This has to be taken into consideration during gravity field analysis by spherical harmonics, which are frequency localising functions. Other mathematical methods using space localising functions or multiscale expansions (space and frequency localisation) can be applied for such problems. Multi-grid methods, which are using space localising kernel functions, are able to solve very efficiently large normal equation systems by an iterative method and are additionally able to generate a well-defined sequence of coarser approximations of the gravity field solution (KUSCHE et al, 1999, 2001a; KUSCHE and RUDOLPH 2000b, 2002; KUSCHE, 2001, 2002a, 2002b; RUDOLPH, 2000, RUDOLPH et al, 2002; THALHAMMER et al, 1999). Multiscale methods based on wavelets as kernel functions are able to analyse the gravity field in a combined space-time domain (FREEDEN, 1999, 2001; FREEDEN et al, 1999a, 1999b, 2001; FREEDEN and MICHEL, 2000, 2001; FREEDEN and PEREVERZEY, 2001; GLOCKNER, 2002, MICHEL, 1999, NUTZ, 2002). By this method, regional

as well as time variable aspects of the gravity field can be investigated more deeply and efficiently.

Earth gravity field models

Several new global Earth gravity field models were published during the reporting period. They were computed in preparation of the CHAMP mission and the most recent models are already based to a large extent on CHAMP observations. First experiences to use low Earth orbiting satellites for gravity field restitution were gained with the GFZ-1 cannonball satellite. The analysis of laser tracking data to this satellite enabled for the first time the determination of some higher degree zonal and resonant order spherical harmonic coefficients up to a maximum degree of 100 (KÖNIG et al, 1999). As preparatory work for CHAMP data analysis new multi-satellite and combined gravity field solutions were determined. The GRIM5-S1 and -S2 satellite-only models are based on various types of tracking data to about 20 satellites. Spherical harmonic coefficients up to degree 99 and order 95 for the static gravity field together with some low degree zonals for secular changes of the gravity field were estimated in a rigorous least squares adjustment (BIANCALE et al, 2000, BIANCALE and SCHWINTZER 2000). The models show a significant improvement with respect to previous solutions and could be regarded as the state of the art prior to the CHAMP mission. A combined gravity field model was computed based on the GRIM5-S1 normal equations, surface gravity data and altimetric derived gravity anomalies. This GRIM5-C1 model, complete to degree and order 120, represents for this frequency range, one of the best available global gravity field models today (GRUBER et al, 2000a). Several high resolution models (up to degree 360) combining full normal equation systems for the long wavelengths (e.g. up to degree 120) and reduced block diagonal systems for the higher degree terms were computed additionally (GRUBER 2000; GRUBER et al, 2000b). Starting with the launch of CHAMP in July 2000 and the availability of GPS satellite-to-satellite tracking data the first CHAMP based gravity field models were computed. The EIGEN-1S model (REIGBER et al, 2002a, 2003) combines 3 months of GPS tracking data with the GRIM5-S1 multi-satellite solution (degree and order 119). The model shows significant improvements with respect to all previous solutions for the long wavelengths. As follow-on a CHAMP only model (EIGEN-2) based on 6 months of reprocessed GPS tracking data was computed (up to degree and order 140) (REIGBER et al, 2002c). Again the model shows strong improvements for the long wavelengths (up to degree 40) compared to any previous gravity field model and represents for this frequency range the state of the art. Further significant improvements can be expected as soon as the first GRACE gravity field models will be released.

Apart from the purely numerical satellite data analysis also some work on global isostatic gravity field modelling was performed. Some specific investigations about the influence of different models of the earth's crust on the gravity field (KUHN, 1999) and about different isostatic models (TSOULIS, 1999a, 1999b, 2001) was done. A purely isostatic gravity field model of the Earth was developed by KABAN et al,

(1999). For this model new data on the density and structure of the Earth's crust, together with data on the age of the lithosphere were used. In another approach it was attempted to compute geopotential correction coefficients from multi-satellite altimeter crossover data (BOSCH et al, 2000) or, the other way around, to use this information for testing the quality of a gravity field model (KLOKOCNIK et al 2000, 2002). These methods are of interest for future gravity field modelling activities (e.g. validation).

The determination of the stationary part of the sea surface topography using new representations of the oceanic geoid derived from the new gravity field models was another working area in the last 4 years. Specifically the impact of the new gravity missions for future sea surface topography models was investigated. It was found that the EIGEN-1S model already shows significant improvements for a derived sea surface topography (GRUBER and STEIGENBERGER, 2003). SCHRÖTER et al, (2002) investigated the impact of the future GOCE mission on the determination of the sea surface topography (see also BOSCH, 2002). Generally it is expected that the new missions will revolutionise the quality of geodetic and oceanographically derived sea surface topography solutions. Also a new method for a joint estimation of the geoid and the sea surface topography was investigated (BLINKEN, 1999; BLINKEN and KOCH, 1999, 2001; LOSCH et al, 2002).

Future prospects

During the next couple of years the analysis of the CHAMP and GRACE mission data will be one of the focal points. Besides the static part of the global gravity field the determination of the time variable gravity field and its interpretation will be one of the main working areas. Several investigations about the impact of mass redistributions within, on and above the Earth on the gravity field were performed (REIGBER et al, 1999a; JOCHMANN et al, 2001). Atmospheric and oceanic mass variations are one of the major sources to be taken into consideration (FÖLDVARY and FUKUDA, 2002; GRUBER et al, 2000c; KUHN, 2002; PETERS, 2001; PETERS et al, 2002; WÜNSCH et al, 2001, 2002). Short term mass variations have to be corrected during data analysis in order to overcome the unequal space-time sampling of the satellite tracks projected on the Earth's surface.

Another focal point is the preparation of the GOCE mission. Considerable work has already been performed during the last years in order to investigate the mission and instrument performance (MÜLLER and OBERNDORFER, 1999A, 1999B; MÜLLER, 2001; OBERNDORFER et al, 1999, 2000, 2002b; OBERNDORFER and MÜLLER, 2002; RUMMEL et al, 2000; SMIT et al, 2000; SNEEUW et al, 2001, 2002), the data processing algorithms, the impact to science applications (RUMMEL, 2002a, 2002b; SNEEUW et al, 2000), the calibration/validation of the products (DENKER, 2002; Müller et al, 2002) and the combination with terrestrial data (KUSCHE et al, 2000). Future work will focus on the preparation and development of efficient algorithms in order to be able to process GOCE high resolution gravity field models with the required accuracy and with reasonable computational efforts. Special emphasis during these developments should

be given to possible synergies with the CHAMP and GRACE missions (GRUBER, 2001b).

References

- AUSTEN G., REUBELT T.: *Räumliche Schwerefeldanalyse aus semi-kontinuierlichen Ephemeriden niedrigfliegender GPS-vermessener Satelliten vom Typ CHAMP, GRACE und GOCE*; Diploma thesis, Geodetic Institute, University of Stuttgart, Germany; (<http://www.uni-stuttgart.de/gi/education/diplomarbeiten/austen+reubelt/titelseite.html>), 2000
- AUSTEN G., GRAFAREND E.W., REUBELT T.: *Analysis of the Earth's Gravitational Field from Semi-Continuous Ephemeris of a Low Earth Orbiting GPS-tracked Satellite of Type CHAMP, GRACE and GOCE*; IAG Symposia Proceedings, No. 125, Vistas for Geodesy in the New Millennium, Ed. Adam, Schwarz, Springer Verlag, 2002
- BALMINO G., RUMMEL R., VISSER P., WOODWORTH P.L.: *Gravity Field and Steady-State Ocean Circulation Mission*; In: The Four Candidate Earth Explorer Core Missions, ESA SP-1233(1), 1999a
- BALMINO G., PEROSANZ F., RUMMEL R., SNEEUW N., SÜNKEL H.: *CHAMP, GRACE and GOCE: Mission Concepts and Simulations*; Bolletino di Geofisica Teorica ed Applicata, Vol. 40, 3-4, 309-319, 1999b
- BIANCALE R., BALMINO G., LEMOINE J.M., MERTY J.C., BARLIER F., EXERTIER P., LAURIN O., GEGOUT P., SCHWINTZER P., REIGBER CH., BODE A., KÖNIG R., MASSMANN F.-H., RAIMONDO J.C., SCHMIDT R., ZHU S.Y.: *A New Global Earth's Gravity Field Model from Satellite Orbit Perturbations: GRIM5-S1*; Geophysical Research Letters, Vol. 27, No. 22, p. 3611-3614, 2000
- BIANCALE R., SCHWINTZER P.: *The GRIM5-S2/C2 Earth Gravity Field Models*; Geophysical Research Abstracts, Vol. 2, EGS 25th General Assembly, 2000
- BLINKEN R.: *Bestimmung von Geoid und Meerestopographie aus Altimeterdaten mittels der adjungierten Methode*; Dissertation, Shaker Verlag, Aachen, 1999
- BLINKEN R., KOCH K.R.: *Estimation of Geoid and Sea Surface Topography From Satellite Altimetry by the Adjoint Method*; Bolletino di Geofisica Teorica ed Applicata, Vol. 40, 3-4, 347-352, 1999
- BLINKEN R., KOCH K.R.: *Geoid and Sea Surface Topography Derived From Ers-1 Altimetry Data by the Adjoint Method*; Stud. Geophys. et Geod., 45, 235-250, 2001
- BOSCH W., KLOKOCNIK J., WAGNER C.A., KOSTELECKY J.: *Geosat and ERS-1 Datum Offsets Relative to Topex/Poseidon Estimated Simultaneously with Geopotential Corrections from Multi-Satellite Crossover Altimetry*; IAG Symposia Proceedings Vol. 120, Towards an Integrated Global Geodetic Observing System, Ed. Rummel, Drewes, Bosch, Hornik, Springer Verlag, 2000
- BOSCH W.: *The Sea Surface Topography and its Impact to Global Height System Definition*; IAG Symposium Proceedings Vol. 124, Vertical Reference Systems, Ed. Drewes, Dodson, Fortes, Sanchez, Sandoval; Springer Verlag, 2002
- CUI CH., LELGEMANN D.: *On non-linear low-low SST Observation Equations for the Determination of the Geopotential based on an analytical Solution*; Journal of Geodesy, Vol. 74, 432-440, 2000

- DENKER H.: *Computation of Gravity Gradients Over Europe for Validation/Calibration of GOCE Data*; In: Proceedings of the 3rd Meeting of the International Gravity and Geoid Commission, Thessaloniki, in print 2002.
- FÖLDVÁRY L., FUKUDA Y.: *Effects of atmospheric Variations on the Marine Geoid determined by forthcoming Gravity Satellite Mission*; IAG Symposia Proceedings, No. 125, Vistas for Geodesy in the New Millennium, Ed. Adam, Schwarz, Springer Verlag, 2002
- FREEDEN W.: *Multiscale Modelling of Spaceborne Geodata*; B.G. Teubner Verlag, Stuttgart, Leipzig, 1999
- FREEDEN W., GLOCKNER O., LITZENBERGER R.: *Multiscale Modelling from Geopotential Data*; Proceedings of International Conference on Multivariate Approximation, Bommerholtz, Wiley, 1999a
- FREEDEN W., GLOCKNER O., THALHAMMER M.: *Multiscale gravitational Field Recovery from GPS Satellite-to-Satellite Tracking*; Studia Geophysica et Geodaetica, Vol. 43, p. 229-264, 1999b
- FREEDEN W., MICHEL V.: *Least-squares Geopotential Approximation by Windowed Fourier Transform and Wavelet Transform*; In: Springer Lecture Notes in Earth Sciences, R. Klees and R. Haagmans, editors, (90): 189-241, 2000
- FREEDEN W., PEREVERZEY S.: *Spherical Tikhonov Regularization Wavelets in Satellite Gravity Gradiometry with random Noise*; Journal of Geodesy, Vol. 74, 730-736, 2001
- FREEDEN W., MICHEL V.: *Basic Aspects of Geopotential Field Approximation from Satellite-to-Satellite Tracking Data*; Math. Meth. In the Appl. Sci., Vol. 24, pp.827-846, 2001
- FREEDEN W., MICHEL V., NUTZ H.: *Satellite-to-Satellite Tracking and Satellite Gradiometry (Advanced Techniques for High-Resolution Geopotential Field Determination)*; AGTM Report No. 236, University of Kaiserslautern, 2001
- FREEDEN W.: *Multiscale Modelling of Goce-data-products*; Proceedings of 1st International GOCE User Workshop; ESA Publication Division, Report WPP-188, 2001
- GERLACH C., SNEEUW N., VISSER P., SVEHLA D.: *CHAMP Gravity Field Recovery with the Energy Balance Approach: First Results*; accepted in Proceedings of first CHAMP Meeting, Potsdam, Germany, to be published 2003a
- GERLACH C., SNEEUW N., VISSER P., SVEHLA D.: *CHAMP Gravity Field Recovery using the Energy Balance Approach*; accepted in Advances in Geosciences, 2003b
- GLOCKNER O.: *On Numerical Aspects of Gravitational Field Modelling from SST and SGG by Harmonic Splines and Wavelets (With Application to CHAMP Data)*; PhD thesis, University of Kaiserslautern, Geomathematics Group. Shaker Verlag Aachen, 2002
- GREINER-MAI H., JOCHMANN H., BARTHELMES F.: *Influence of possible Inner-Core Motions on the polar Motion and the Gravity Field*; Physics of the Earth and Planetary Interiors, Vol. 117, 81-93, 2000
- GRUBER TH.: *Global Gravity Field Modelling*; in: National Report of the Federal Republic of Germany on the Geodetic Activities in the Years 1995-1999; compiled by: B. Heck, R. Rummel, E. Groten, H. Hornik; DGK Reihe B, Heft Nr. 308, München 1999
- GRUBER TH.: *Hochauflösende Schwerefeldbestimmung aus Kombination von terrestrischen Messungen und Satellitendaten über Kugelfunktionen*; Scientific Technical Report STR00/16, GFZ Potsdam, 2000
- GRUBER TH., BODE A., REIGBER CH., SCHWINTZER P., BALMINO G., BIANCALE R., LEMOINE J.M.: *GRIM5-C1: Combination Solution of the Global Gravity Field to Degree and Order 120*; Geophysical Research Letters, Vol. 27 No. 24, p. 4005-4008, 2000a
- GRUBER TH., REIGBER CH., SCHWINTZER P.: *The 1999 GFZ pre-CHAMP High Resolution Gravity Model*; IAG Symposia Proceedings, Vol. 121, Geodesy Beyond 2000, Ed. Schwarz, Springer Verlag, 2000b
- GRUBER TH., REIGBER CH., WÜNSCH J.: *Estimation of Ocean Mass Redistribution by Means of Altimetry and Circulation Models and its Impact on the Gravity Field*; IAG Symposia Proceedings Vol. 120, Towards an Integrated Global Geodetic Observing System, Ed. Rummel, Drewes, Bosch, Hornik; Springer Verlag, 2000c
- GRUBER TH.: *High-Resolution Gravity Field Modeling with full Variance-Covariance Matrices*; Journal of Geodesy, Vol. 75, 505-514, 2001a
- GRUBER TH.: *Identification of Processing and Product Synergies for Gravity Missions in View of the CHAMP and GRACE Science Data System Developments*; Proceedings of 1st International GOCE User Workshop; ESA Publication Division, Report WPP-188, 2001b
- GRUBER TH., STEIGENBERGER P.: *Impact of New Gravity Field Missions for Sea Surface Topography Determination*; In: Proceedings of the 3rd Meeting of the International Gravity and Geoid Commission, Thessaloniki, in print 2003
- HESS D., KELLER W.: *Gradiometrie mit GRACE, Teil I und II*; Zeitschrift für Vermessungswesen; Vol. 5/99, pp. 137-144; Vol. 7/99, pp. 205-211, 1999
- ILK K.H.: *Envisaging a new Era of Gravity Field Research*; IAG Symposia Proceedings Vol. 120, Towards an Integrated Global Geodetic Observing System, Ed. Rummel, Drewes, Bosch, Hornik, Springer Verlag, 2000
- ILK K.H.: *Energy Relations for the Motion of two Satellites within the Gravity Field of the Earth*; IAG Symposia Proceedings, Vol. 123, Ed. Sideris, pp. 129-135, Springer Verlag, 2002
- ILK K.H., KUSCHE J., RUDOLPH S.: *A Contribution to Data Combination in ill-posed downward Continuation Problems*; Journal of Geodynamics, Vol. 33, 75-99, 2002
- ILK K.H.: *Energy Relations for Satellite-to-Satellite Motions*; Geodesy, The Challenge of the Third Millennium; Ed. Grafarend, Krunmm, Schwarze; Springer Verlag, 2003
- JOCHMANN H., REIGBER CH., GREINER-MAI H., WÜNSCH J., BARTHELMES F.: *Geophysikalische Prozesse, Erdrotation und zeitlich variables Schwerefeld*; Scientific Technical Report STR 01/11; GFZ Potsdam, 2001
- KABAN M.K., SCHWINTZER P., TIKHOTSKY A.: *A Global Isostatic Gravity Model of the Earth*; Geophysical Journal International, Vol. 136, pp. 519-536, 1999
- KLEES R., KOOP R., VISSER P., VAN DEN IJSSEL J., RUMMEL R.: *Data Analysis for the GOCE Mission*; IAG Symposia Proceedings, No. 121, Geodesy beyond 2000, Ed. Schwarz, Springer Verlag, 2000
- KLOKOCNIK J., REIGBER CH., SCHWINTZER P., WAGNER C.A., KOSTELECKY J.: *Evaluation of pre-CHAMP Gravity Models GRIM5-S1 and GRIM5-C1 with Satellite Crossover*

- Altimetry*; Scientific Technical Report STR00/22, GFZ Potsdam, 2000
- KLOKOCNIK J., REIGBER CH., SCHWINTZER P., WAGNER C.A., KOSTELECKY J.: *Evaluation of pre-CHAMP Gravity Models GRIM5-S1 and GRIM5-C1 with Satellite Crossover Altimetry*; Journal of Geodesy, Vol. 76, 189-198, 2002
- KOCH K.R., KUSCHE J.: *Regularization of Geopotential Determination from Satellite Data by Variance Components*; Journal of Geodesy, Vol. 76, 259-268, 2002
- KÖNIG R., CHEN Z., REIGBER CH., SCHWINTZER P.: *Improvement in global Gravity Field Recovery using GFZ-1 Satellite Laser Tracking Data*; Journal of Geodesy, Vol. 73, 398-406, 1999
- KUHN M.: *The Influence of different Crust Models on the Gravity Field of the Earth*; Bolletino di Geofisica Teorica ed Applicata, Vol. 40, 3-4, 555-562, 1999
- KUHN M.: *Geoid Variations due to mean Sea Level Variations*; IAG Symposia Proceedings Vol. 124, Vertical Reference Systems, Ed. Drewes, Dodson, Fortes, Sanchez, Sandoval; Springer Verlag, 2002
- KUSCHE J., ILK K.H., RUDOLPH S.: *Two-Step Data Analysis for future Satellite Gravity Field Solutions: A Simulation Study*; Bolletino di Geofisica Teorica ed Applicata, Vol. 40, 3-4, 261-266, 1999
- KUSCHE J., ILK K.H., RUDOLPH S.: *Impact of terrestrial Data on future Satellite Gravity Field Solutions*; IAG Symposia Proceedings Vol. 120, Towards an Integrated Global Geodetic Observing System, Ed. Rummel, Drewes, Bosch, Hornik, Springer Verlag, 2000
- KUSCHE J., RUDOLPH S.: *The multigrid Method for Satellite Gravity Field Recovery*; IAG Symposia Proceedings, Vol. 121, Geodesy Beyond 2000, Ed. Schwarz, Springer Verlag, 2000
- KUSCHE J.: *Implementation of multigrid Solvers for Satellite Gravity Anomaly Recovery*; Journal of Geodesy, Vol. 74, 773-782, 2001
- KUSCHE J., RUDOLPH S., FEUCHTINGER M., ILK KH.: *Gradiometric Data Analysis using icosahedral Grids*, Proceedings of 1st International GOCE User Workshop, ESA Publication Division Report WP-188, 2001a
- KUSCHE J., KLEES R.: *On the Regularization Problem in Gradiometric Data Analysis From Goce*, Proceedings of 1st Int Goce User Workshop, Esa Publication Division, Report Wp-188, 2001b
- KUSCHE J., RUDOLPH S.: *Satellite Gravity Anomaly Recovery using multigrid Methods*; IAG Symposia Proceedings, Vol. 123, Ed. Sideris, p. 91-96, Springer Verlag, 2002a
- KUSCHE J., KLEES R.: *On the Regularization Problem in Gravity Field Determination from Satellite gradiometric Data*; IAG Symposia Proceedings, No. 125, Vistas for Geodesy in the New Millenium, Ed. Adam, Schwarz, Springer Verlag, 2002b
- KUSCHE J., KLEES R.: *Regularization of Gravity Field Estimation from Satellite Gravity Gradients*; Journal of Geodesy, Vol. 76, 359-368, 2002c
- KUSCHE J.: *On fast multigrid Iteration Techniques for the Solution of normal Equations in Satellite Gravity Recovery*; Journal of Geodynamics, Vol. 33, 173-186, 2002a
- KUSCHE J.: *Inverse Probleme bei der Gravitationsfeldbestimmung mittels SST- und SGG- Satellitenmissionen*, Deutsche Geodätische Kommission, Heft C 548, München 2002b
- LEHMANN R., KLEES R.: *Numerical Solution of geodetic Boundary Value Problems using a global Reference Field*; Journal of Geodesy, Vol. 73, 543-554, 1999
- LEHMANN R.: *Altimetry-Gravimetry Problems with free vertical Datum*; Journal of Geodesy, Vol. 74, 327-334, 2000
- LOSCH M., SLOYAN B., SCHRÖTER J., SNEEUW N.: *Box inverse Models, Altimetry and the Geoid: Problems with the Omission Error*; Journal of Geophysical Research, Vol. 107, C7, 2002
- MARCHENKO A.N., SCHWINTZER P.: *Principal Axes and principal Moments of Inertia from recent Satellite Gravity Field Solutions*; IAG Symposia Proceedings No. 125, Vistas for Geodesy in the New Millenium, Ed. Adam, Schwarz, Springer Verlag, 2002a
- MARCHENKO A.N., SCHWINTZER P.: *The Earth's Tensor of Inertia – Estimation from Recent Gravity Field Solutions*; Journal of Geodesy, accepted 5/2002b
- MICHEL V.: *A Multiscale Method for the Gravimetry Problem – Theoretical and Numerical Aspects of Harmonic and Anharmonic Modelling*; Doctoral Thesis, University of Kaiserslautern, Geomathematics Group; Shaker Verlag, Aachen, 1999
- MÜLLER J., OBERNDORFER H.: *Validation of GOCE Simulation*; IPAG/FESG Report No. 1, Technical University Munich, 1999a
- MÜLLER J., OBERNDORFER H.: *Simulation of the GOCE Gradiometer Mission*; Artificial Satellites, Vol. 34, No. 1 pp. 41-55, 1999b
- MÜLLER J.: *Die Satellitengradiometriemission GOCE*; Deutsche Geodätische Kommission, Heft C541, München, 2001
- MÜLLER J., JARECKI F., WOLF K.I.: *External Calibration and Validation of GOCE Gradients*; In: Proceedings of the 3rd Meeting of the International Gravity and Geoid Commission, Thessaloniki, in print 2002.
- NUTZ H.: *A Unified Setup of Gravitational Field Observables*; Doctoral Thesis, University of Kaiserslautern, Geomathematics Group; Shaker Verlag, Aachen, 2002
- OBERNDORFER H., DOROBANTU R., GERLACH C., MÜLLER J., RUMMEL R., SNEEUW N., KOOP R., VISSER P., HOYNG P., SELIG A., SMIT M.: *GOCE Sensor Combination and Error Analysis*; Bolletino di Geofisica Teorica ed Applicata, Vol. 40, 3-4, 303-307, 1999
- OBERNDORFER H., MÜLLER J., DOROBANTU R., GERLACH C., RUMMEL R., SNEEUW N., KOOP R., VISSER P., HOYNG P., SELIG A., SMIT M.: *Simulation of the GOCE Gravity Field Mission*; IAG Symposia Proceedings Vol. 120, Towards an Integrated Global Geodetic Observing System, Ed. Rummel, Drewes, Bosch, Hornik, Springer Verlag, 2000
- OBERNDORFER H., MÜLLER J., GRUNWALDT L.: *On the Potential of a combined Use of CHAMP Star Tracking and Accelerometry*; IAG Symposia Proceedings, No. 125, Vistas for Geodesy in the New Millenium, Ed. Adam, Schwarz, Springer Verlag, 2002a
- OBERNDORFER H., MÜLLER J., RUMMEL R., SNEEUW N.: *A Simulation Tool for the new Gravity Field Satellite Missions*; Advances in Space Research, Vol. 30, 2, 227-232, 2002b
- OBERNDORFER H., MÜLLER J.: *GOCE closed-loop Simulation*; Geophysical Journal International, Vol. 33, 53-63, 2002

- PETERS T.: *Zeitliche Variationen des Gravitationsfeldes der Erde*; IAPG/FESG Report No. 12, Technical University Munich, 2001
- PETERS T., MÜLLER J., SNEEUW N.: *Temporal Variations in the Gravity Field*; Deutsche Geodätische Kommission Reihe A, Nr. 118, pp. 133-140, München, 2002
- REIGBER CH., BARTHELMES F., GREINER-MAI H., GRUBER TH., JOCHMANN H., WÜNSCH J.: *Temporal Gravity Field Variations from oceanic, atmospheric and inner core Mass Redistributions and their Sensitivity to new Gravity Missions CHAMP and GRACE*; Bolletino di Geofisica Teorica ed Applicata, Vol. 40, 3-4, 329-340, 1999a
- REIGBER CH., SCHWINTZER P., LÜHR H.: *The CHAMP Geopotential Mission*; Bolletino di Geofisica Teorica ed Applicata, Vol. 40, 3-4, 285-289, 1999b
- REIGBER CH., LÜHR H., SCHWINTZER P.: *Status of Champ Mission*; IAG Symposia Proceedings Vol. 120, Towards an Integrated Global Geodetic Observing System, Ed. Rummel, Drewes, Bosch, Hornik, Springer Verlag, 2000
- REIGBER CH., BALMINO G., SCHWINTZER P., BIANCALE R., BODE A., LEMOINE J.M., KÖNIG R., LOYER S., NEUMAYER H., MARTY J.C., BARTHELMES F., PEROSANZ F., ZHU S.Y.: *A high Quality Global Gravity Field Model from CHAMP GPS Tracking Data and Accelerometry (EIGEN-1S)*; Geophysical Research Letters, Vol. 29, 14, 2002a
- REIGBER CH., LÜHR H., SCHWINTZER P.: *CHAMP Mission Status*; Advances in Space Research, Vol. 30, 2, pp. 129-134, 2002b
- REIGBER CH., SCHWINTZER P., NEUMAYER K.H., BARTHELMES F., KÖNIG R., FÖRSTE CH., BALMINO G., BIANCALE R., LEMOINE J.M., LOYER S., BRUINSMA S., PEROSANZ F., FAYARD T.: *The CHAMP-Only EIGEN-2 Earth Gravity Field Model*; Advances Space Research, submitted Nov. 2002c
- REIGBER CH., BALMINO G., SCHWINTZER P., BIANCALE R., BODE A., LEMOINE J.M., KÖNIG R., LOYER S., NEUMAYER H., MARTY J.C., BARTHELMES F., PEROSANZ F., ZHU S.Y.: *Global Gravity Field Recovery using solely GPS Tracking and Accelerometer Data from CHAMP*; Space Science Reviews, Kluwer Academic Publishers, Vol. in print, 2003
- RENTSCH M., GRUBER TH., ANZENHOFER M.: *A global Grid of high Resolution Gravity Anomalies based on Geosat and ERS-1 Altimetry*; Bolletino di Geofisica Teorica ed Applicata, Vol. 40, 3-4, 387-394, 1999
- RUDOLPH S.: *Regionale und Globale Gravitationsfeldanalyse Hochauflösender Satellitendaten mittels Mehrgitterverfahren*, Deutsche Geodätische Kommission, Heft C528, München 2000
- RUDOLPH S., KUSCHE J., ILK K.H.: *Investigations on the polar Gap Problem in ESA's Gravity Field and steady State Ocean Circulation Explorer Mission (GOCE)*; Journal of Geodynamics, Vol. 33, 65-74, 2002
- RUMMEL R., REIGBER CH.: *Beobachtung des Systems Erde aus dem Weltraum*; Kapitel II. In: Geotechnologien, Ed. Emmermann, Harjes, Seifert, Seibold, Thiede, Wellmer; Senatskommission für Geowissenschaftliche Gemeinschaftsforschung der DFG, 1999
- RUMMEL R.: *Bright Prospects for a significant Improvement of the Earth's Gravity Field Knowledge*; Marine Geodesy, Vol. 23, 3, pp. 219-220, 2000
- RUMMEL R., MÜLLER J., OBERNDORFER H., SNEEUW N.: *Satellite Gravity Gradiometry with GOCE*; IAG Symposia Proceedings Vol. 120, Towards an Integrated Global Geodetic Observing System, Ed. Rummel, Drewes, Bosch, Hornik, Springer Verlag, 2000
- RUMMEL R.: *Global Unification of Height Systems and GOCE*; IAG Symposia Proceedings, Vol. 123, Ed. Sideris, p. 13-20, Springer Verlag, 2002a
- RUMMEL R.: *Space Geodesy and Earth Sciences*; IAG Proceedings, Symposium No. 125, Vistas for Geodesy in the New Millennium, Ed. Adam, Schwarz, Springer Verlag, 2002b
- RUMMEL R., BALMINO G., JOHANESSEN J., VISSER P., WOODWORTH P.: *Dedicated Gravity Field Missions - Principles and Aims*; Journal of Geodynamics, Vol. 33, 3-20, 2002
- RUMMEL R.: *How to climb the Gravity Wall*; Space Science Reviews, Kluwer Academic Publishers, Vol. in print, 2003
- SCHÄFER, C.: *Space Gravity Spectroscopy-the Sensitivity Analysis of Gps-tracked Satellite Missions (Case Study Champ)*, Deutsche Geodätische Kommission, Bayerische Akademie Der Wissenschaften, Report C 534, 2001
- SCHÄFER CH., GRAFAREND E.: *On the Determination of gravitational Information from GPS tracked Satellite Missions; Artificial Satellites*, Vol. 37, 2, 31-49, 2002
- SCHNEIDER M.: *Zur Methodik der Gravitationsfeldbestimmung mit Erdsatelliten*; IAPG/FESG Report No. 15, Technical University Munich, 2002
- SCHRÖTER, J., LOSCH, M., SLOYAN, B.: *Impact of the Gravity Field Andsteady-state Ocean Circulation Explorer (Goce) Mission on Ocean Circulation Estimates. Volume and Heat Transports Across Hydrographic Sections of Unequally Spaced Stations*, Journal of Geophysical Research, 107 (C2), 4-1 Pp. 4-20, 2002
- SCHUH W.D.: *The Processing of band-limited Measurements: Filtering Techniques in the Least Squares Context and in the Presence of Data Gaps*; Space Science Reviews, Kluwer Academic Publishers, Vol. in print, 2003
- SCHWINTZER P., KANG Z., PEROSANZ F.: *Accelerometry aboard CHAMP*; IAG Symposia Proceedings Vol. 120, Towards an Integrated Global Geodetic Observing System, Ed. Rummel, Drewes, Bosch, Hornik, Springer Verlag, 2000
- SCHWINTZER, P.: *Globale Schwerefeldbestimmung aus Satellitenbahnstörungen: Status, Anwendung und Entwicklungsmöglichkeiten mit der CHAMP-Satellitenmission*; In: Caspary, Heister, Schödlbauer, Welsch (Hrsg.): 25 Jahre Inst. für Geodäsie, Wissenschaftliche Beiträge und Berichte; Schriftenreihe Studiengang Geodäsie und Geoinformation der UniBw, Heft 60-1, 305-316, 2000
- SCHWINTZER P., REIGBER CH.: *The Contribution of GPS Flight Receivers to Global Gravity Field Recovery*; Journal of Global Positioning Systems 1 (1), 61-63, 2002a
- SCHWINTZER P., REIGBER CH.: *Das Potsdamer Geoid – Satelliten erkunden das Schwerefeld der Erde*; Sterne und Weltraum 41 (8), 24-31, 2002b
- SMIT M., KOOP R., VISSER P., VAN DEN ISSSEL J., SNEEUW N., MÜLLER J., OBERNDORFER H.: *GOCE End-to-End Performance Analysis*; Final Report, ESTEC Contract No.12735/98/NL/GD, 2000
- SNEEUW N.: *A semi-analytical Approach to Gravity Field Analysis from Satellite Observations*; Deutsche Geodätische Kommission Reihe C, Heft Nr. 527, München, 2000

- SNEEUW N., GERLACH C., MÜLLER J., OBERNDORFER H., RUMMEL R.: *Fundamentals and Applications of the Gravity Field Mission Goce*, Iag Symposia Proceedings Vol. 120, Towards An Integrated Global Geodetic Observing System, Ed. Rummel, Drewes, Bosch, Hornik, Springer Verlag, 2000
- SNEEUW N., DOROBANTU R., GERLACH C., MÜLLER J., OBERNDORFER H., RUMMEL R., KOOP R., VISSER P., HOYNG P., SELIG A., SMIT M.: *Simulation of the GOCE Gravity Field Mission*; In: Proceedings of the Hotine-Marussi Symposium, held in Trento, Italy, Sept. 14-17, 1998, IAG Symposia Proceedings No. 122, pp.14-20, Springer Verlag, 2001
- SNEEUW N.: *Dynamical Satellite Geodesy on the Torus: Block-Diagonality from a semi-analytical Approach*; IAG Symposia Proceedings, Vol. 123, Ed. Sideris, p. 137-142, Springer Verlag, 2002
- SNEEUW N., VAN DEN ISSEL J., KOOP R., VISSER P., GERLACH C.H.: *Validation of fast Pre-Mission Error Analysis of the GOCE Gradiometry Mission by a full Gravity Field Recovery Simulation*; Journal of Geodynamics, Vol. 33, 43-52, 2002
- SNEEUW N., GERLACH C., SVEHLA D., GRUBER C.: *A first Attempt at Time-variable Gravity Recovery from CHAMP using the Energy Balance Approach*; In: Proceedings of the 3rd Meeting of the International Gravity and Geoid Commission, Thessaloniki, in print 2003
- STRAKHOV V.N., SCHÄFER U., STRAKHOV A.V.: *Improved analytical Approximations of the Earth's gravitational Field*; IAG Symposia Proceedings, Vol. 121, Ed. Schwarz, Geodesy Beyond 2000; Springer Verlag, 2000
- TAPLEY CH., REIGBER CH.: *GRACE: A Satellite-To-Satellite Tracking Geopotential Mapping Mission*; Bolletino di Geofisica Teorica ed Applicata, Vol. 40, 3-4, 291-291, 1999
- THALHAMMER M., FREEDEN W., GLOCKNER O.: *Multiscale gravitational Field Recovery from GPS Satellite-to-Satellite Tracking*; Studia geoph. Et geod., 43, pp. 229-264, 1999
- TSOULIS D.: *Spherical harmonic Computations with topographic/isostatic Coefficients*; IPAG/FESG No. 3, Technical University Munich, 1999a
- TSOULIS D.: *Analytical and numerical Methods in Gravity Field Modelling of ideal and real Masses*; Deutsche Geodätische Kommission, Reihe C, Heft Nr. 510, München, 1999b
- TSOULIS D.: *A Comparison between the Airy/Heiskanen and the Pratt/Hayford isostatic Models for the Computation of Potential Harmonic Coefficients*; Journal of Geodesy 74: 637-643, 2001
- VISSER P., RUMMEL R., BALMINO G., SÜNKEL H., JOHANESSEN J., AGUIRRE M., WOODWORTH P., LE PROVOST C., TSCHERNING C., SABADINI R.: *The European Earth Explorer Mission GOCE: Impact for the Geosciences*; Ice Sheets, Sea Level and the Dynamic Earth, Geodynamics Series 29, American Geophysical Union, pp. 95-107, 2002
- VISSER P., SNEEUW N., GERLACH C.: *Energy Integral Method for Gravity Field Determination from Satellite Orbit Coordinates*; accepted in Journal of Geodesy, 2003
- WÜNSCH J., THOMAS M., GRUBER TH.: *Simulation of oceanic bottom Pressure for Gravity Space Missions*; Geophysical Journal International, Vol. 147, 428-434, 2001
- WÜNSCH J., THOMAS M., GRUBER TH.: *Simulationen des ozeanischen Bodendrucks*; Deutsche Geodätische Kommission Reihe A, Nr. 118, pp. 141-147, München, 2002

Regional and local gravity field modelling

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1. Modelling techniques

The theory of geodetic boundary value problems is of fundamental importance for gravity field modelling. NOVAK et al. (2001) and NOVAK and HECK (2002) discuss boundary value problems for the computation of the geoid from airborne gravity data by introducing the concept of a band limited geoid; the studies include the mathematical formulation, computer realization and testing by actual airborne data. A special topic of this work is the use of Helmert's second method of condensation, which is discussed in more detail in HECK (2002). The spheroidal fixed-free two-boundary-value problem for geoid determination is studied in GRAFAREND et al. (1999). An ellipsoidal Bruns formula is derived in ARDALAN and GRAFAREND (2001a), and a normal gravity formula, accurate to the sub-nanoGal level, is derived in ARDALAN and GRAFAREND (2001b). The Somigliana-Pizetti minimum distance telluroid mapping is evaluated in ARDALAN (1999) and ARDALAN et al. (2002), using the state of Baden-Württemberg (Germany) and East Germany as test areas. A new analytical approximation method, that is suitable to represent the Earth's gravity field on a regional as well as on a global scale, is described in STRAKHOV et al. (1999a, 1999b, 1999c, 2000, 2001) and SCHÄFER et al. (2001). The method is applied for the modelling of the height reference surface of East Germany in SCHÄFER (2001). Temporal variations of the deformable Earth are investigated in GRAFAREND (2000) and GRAFAREND et al. (2000).

The use of geostatistical methods for gravity field modelling and geophysical interpretation of terrestrial torsion balance measurements in northern Germany is investigated in MENZ (2000), MENZ and KNOSPE (2001 and 2002), and KNOSPE (2002). As one gravity field quantity, the geoid is derived from the torsion balance data, and the result is compared with gravimetric modelling. Furthermore, problems related to the relative and absolute orientation, model deformations, and smoothing properties are discussed.

Significant progress was also made in the theory and application of wavelets. This is documented in several dissertation theses (BAYER, 2000; BETH, 2000; GLOCKNER, 2002; LITZENBERGER, 2002; MAIER, 2002; MICHEL, 1999; NUTZ, 2002), the textbook from FREEDEN (1999), and special publications in journals (FREEDEN, 2001a and 2001b; FREEDEN et al., 1999a and 1999b; FREEDEN and HESSE, 2002; FREEDEN and MAIER, 2002; FREEDEN and MICHEL, 1999, 2000 and 2001; FREEDEN et al., 2001 and 2002, FREEDEN and PEREVERZEV, 2001; MAIER and MAYER, 2003).

The textbooks on geodesy and gravimetry, published by TORGE (1999, 2000, 2001, and 2002), cover also many topics related to local and regional gravity field modelling. Moreover, the Festschrift TORGE (2001) contains contributions to geoid determination after the first satellite gravity field missions, tidal effects, the height datum problem, and airborne gravimetry.

2. Digital terrain models

Digital terrain models play an important role for the modelling of short wavelength components of the gravity field. Of special importance are the results from the SRTM (Shuttle Radar Topography Mission). The terrain models derived from this mission will cover a large part of the Earth's surface and are expected to be of high and homogeneous quality. An evaluation of first SRTM results in several test areas in Lower Saxony is presented in HEIPKE and KOCH (2002), HEIPKE et al. (2002), and KOCH et al. (2002a, 2002b).

A thorough study of terrain effect computations by analytical and numerical methods is provided in TSOULIS (1999a). The study proposes to combine numerical integration in an inner zone with Fourier expansions in the outer zone. Further details on terrain effect computations and practical tests in the Bavarian Alps can be found in TSOULIS (1999b, 2000, and 2001), and TSOULIS and PETROVIC (2001). The computation of terrain corrections in a moving tangent space and the effect of planar approximations is studied in GRAFAREND and HANKE (2001). The generation of digital terrain models by triangular Bezier patches is investigated in HÄHNLE and GRAFAREND (2002).

3. Geophysical investigations

Gravity data acquisition projects and geophysical interpretations were completed in the central Andes (Chile, Bolivia, Argentina), Jordan, several areas in Germany, and the Eastern Alps. The data processing with station separations down to about 5 km, the computation of terrain reductions, and the geophysical interpretation by means of 3D forward modelling of geoidal undulations, gravity, and its derivatives by the software IGMAS are documented in BRAITENBERG et al. (2000 and 2002), CHOI (2000), EBBING (2002), EBBING and GÖTZE (2001), EBBING et al. (2001a and 2001b), GIESE et al. (2000), GOLTZ (2001), GÖTZE and KRAUSE (2002), GÖTZE and SCHMIDT (2002), KRAWCZYK et al. (2000), KUDER (2002), LI and GÖTZE (2001), OMARINI et al. (2001), OTT et al. (2002), and WITTKOPF (2002).

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Further geophysical gravity field interpretations based on gravity observations are presented for the salt dome Arendsee (GABRIEL and RAPPILBER, 1999), an area south of the Harz mountains (GABRIEL et al., 2001), a tertiary maar near Baruth (GABRIEL et al., 2000), and for Pleistocene valleys in northern Germany with emphasis on ground water deposits (WIEDERHOLD et al., 2001, 2002a, and 2002b).

The preparation and homogenization of seismic data for a fjord region in East Greenland is described in SCHMIDT-AURSCH (2002). The re-processed seismic data is combined with Bouguer anomaly data for a geophysical interpretation of the upper crust. The crustal structure for the area is compared with other regions of similar age.

Sea-level changes in Southeast Alaska up to 4 cm/year and corresponding geoid changes are modelled by viscoelastic Earth models in BÖLLING et al. (2001). The comparison of the calculated with the observed sea-level changes shows that the observations can be explained by isostasy only to a small part of a few mm/year. The total atmospheric influence with elastic Earth models on high-accuracy gravity measurements is studied in HAGEDOORN et al. (2001), aiming at the reduction of superconducting gravity meter records.

4. Projects and results

The introduction of a new World Geodetic Datum 2000 is suggested in GRAFAREND and ARDALAN (1999), using the fundamental parameters W_0 , GM, J_2 , W, for the system definition. This work is extended to time variations of the fundamental parameters (especially W_0) in ARDALAN and GRAFAREND (1999), and GRAFAREND and ARDALAN (2002).

The application of the gradiometry concept to the GRACE satellite mission is evaluated in two contributions from HESS and KELLER (1999a and 1999b), considering the GRACE satellite pair as a one-axis gradiometer with a large baseline. SCHÄFER and GRAFAREND (2002) elaborate on the determination of gravitational information from GPS-tracked satellite missions. New ultra-high degree global spherical harmonic models ($l_{\max}=1800$) are presented in WENZEL (1999). These models are valuable for local and regional gravity field computations and can serve as a basis for synthetic gravity field models to be used, e.g., for software testing, etc.

The Institut für Erdmessung, University of Hannover, continued its work as the computing center for the European geoid. Preparations were done for an update of the existing solution EGG97, considering improved global gravity field models, improved or new digital terrain and gravity data sets, GPS/levelling data, and refined computing techniques. The use of the existing model EGG97 for GPS heighting applications is discussed in DENKER (2002b) and TORGE and DENKER (1999). An evaluation of the EGG97 in Lithuania is reported in DENKER and PARSELIUNAS (1999). The effect of datum inconsistencies in position, gravity and height on European geoid computations is discussed in DENKER (2001 and 2002a). At present, long wavelength errors at the level of 0.1 to 1.0 ppm exist in most gravimetric geoid models due to corresponding errors in the global models and the terrestrial data, which, hopefully, can be reduced by the new satellite gravity field missions. At

present, however, the combination of the gravimetric models with GPS/levelling data is the only practical and powerful solution. Two different combination techniques, namely collocation and point mass modelling, were tested for this purpose in East Germany (DENKER et al., 2000). The results show that the computed combined height reference surface has an accuracy of about 1 cm. Furthermore, the gravity and terrain data sets, collected within the framework of the European geoid project, were used for upward continuation to derive radial gravity gradients at satellite altitude for the calibration/validation of GOCE data (DENKER, 2002c).

A detailed study on local gravity field modelling in a mountainous area of the Bavarian Alps is given in FLURY (1999 and 2002). Furthermore, a technique for high resolution regional geoid computation is evaluated for the state of Baden-Württemberg (Germany) in ARDALAN and GRAFAREND (2001c).

The processing of marine gravity observations (around Chile, Argentina, Namibia, and South Africa), the evaluation and geophysical interpretation of the results, and the improvement of a sea gravity meter system KSS31M for car-based and airborne gravimetry is discussed in BGR (2003). The merging and crossover adjustment of marine gravity observations from different sources is also studied in the dissertation thesis of BEHREND (1999); the adjusted ship data are then combined with altimetric results for the computation of precise marine geoid models. Similar studies around Japan can be found in Kuroishi and Denker (2001a and 2001b); here the situation is more difficult due to the complicated tectonic setting and strong ocean currents. Airborne gravity data in the Skagerrak are used together with terrestrial gravity data and different computation techniques for precise geoid determination in MARCHENKO et al. (2001 and 2002).

Several publications are related to the determination of vertical deflections using CCD technology. A digital zenith camera, in combination with a GPS receiver for timing and positioning, and an automated real-time processing strategy is discussed in HIRT (2001), HIRT and SEEBER (2002), HIRT and BÜRKI (2002), HIRT (2002), and SCHÖBEL et al. (2000). The main applications of the CCD camera systems are local geoid determination and local geodetic network computations. Moreover, GRAFAREND and AWANGE (2000) derive vertical deflections by a combination of GPS/LPS measurements.

References

- ARDALAN, A.: *Somigliana-Pizetti minimum distance telluroid mapping*. In: KRUMM, F., SCHWARZE, V.S. (Eds.): Quo vadis geodesia ...? Festschrift for Erik W. Grafarend on the occasion of his 60th birthday. Schriftenreihe der Institute des Studiengangs Geodäsie und Geoinformatik, Technical Reports, Department of Geodesy and Geoinformatics, 1999.6, Stuttgart University, 1999.
- ARDALAN, A., GRAFAREND, E.: *A first test of \hat{W}_0 , the time variations of W_0 based on three GPS campaigns of the Baltic Sea Level Project*. In: POUTANEN, M., KAKKURI, J. (Eds.): Final Results of the Baltic Sea Level 1997 GPS Campaign, Report 99:4, The Finnish Geodetic Institute, Kirkkonummi, 93-113, 1999.

- ARDALAN, A., GRAFAREND, E.: *Ellipsoidal geoidal undulations (ellipsoidal Bruns formula): case studies*. J. Geod. 75, 544-552, 2001a.
- ARDALAN, A., GRAFAREND, E.: *Somigliana-Pizzetti gravity: the international gravity formula accurate to the sub-nanoGal level*. J. Geod. 75, 424-437, 2001b.
- ARDALAN, A., GRAFAREND, E.: *High resolution regional geoid computation*. In: SIDERIS, M.G. (Ed.): Gravity, Geoid and Geodynamics 2000, IAG Symposia, Vol. 123, 301-311, Springer-Verlag, Berlin Heidelberg New York, 2001c.
- ARDALAN, A., GRAFAREND, E., IHDE, J.: *Molodensky potential telluroid based on a minimum-distance map*. Case study: the quasi-geoid of East Germany in the World Geodetic Datum 2000. J. Geod. 76, 127-136, 2002.
- BAYER, M.: *Geomagnetic Field Modelling From Satellite Data by First and Second Generation Wavelets*. PhD thesis, University of Kaiserslautern, Geomathematics Group, Shaker Verlag, Aachen, 2000.
- BEHREND, D.: *Untersuchungen zur Schwerefeldbestimmung in den europäischen Randmeeren*. Diss., Wiss. Arb. d. Fachr. Verm.wesen, Nr. 229, Hannover, 1999.
- BETH, S.: *Multiscale Approximation by Vector Radial Basis Functions on the Sphere*. PhD thesis, University of Kaiserslautern, Geomathematics Group, Shaker Verlag, Aachen, 2000.
- BGR: *Referat B3.17, Marine nichtseismische Messverfahren, Methodenentwicklung*. <http://www.bgr.de/b317/homepage.htm>
- BÖLLING, K., HAGEDOORN, J.M., WOLF D., GRAFAREND, E.: *Berechnung eislastinduzierter Vertikalbewegungen und Geoidänderungen in Südostalaska mit Hilfe viskoelastischer Erdmodelle*. Report STR 01/08, Geo-Forschungszentrum Potsdam, Potsdam, 2001.
- BRAITENBERG, C., EBBING, J., GÖTZE, H.-J.: *Inverse modeling of Elastic thickness by convolution method – the Eastern Alps as a case example*. Earth and Planetary Science Letters 202, 387-404, 2002.
- BRAITENBERG, C., GÖTZE, H.-J., JAHR, T., JENTZSCH, G., SCHMIDT, S., STRYKOWSKI, G. (Eds.): *Potential fields in geodesy, geophysics and geology*. Inversion and interpretation of gravity and magnetic anomalies on all scales, case histories. Physics and Chemistry of the Earth, 343-393, 2000.
- CHOI, S.-CH.: *Horizontale und vertikale Dichtezonierung in den Varisziden am Beispiel des Erzgebirges*. Diss. FB Geowissenschaften, FU Berlin, Berliner Geowissenschaftliche Abhandlungen, Reihe B, Bd. 38, 105 p., 2000.
- DENKER, H.: *On the Effect of Datum Inconsistencies in Gravity and Position on European Geoid Computations*. CD-ROM Proceed., IAG 2001 Scientific Assembly, Vistas for Geodesy in the New Millennium, Budapest, Hungary, 2-7 Sept. 2001.
- DENKER, H.: *Einfluß von Datumsinkonsistenzen bei der Schwerefeldmodellierung*. Sitzung des Arbeitskreises Theoretische Geodäsie der Deutschen Geodätischen Kommission (DGK), Bonn, 09.07.2002, <http://www.geod.uni-bonn.de/index.html>
- DENKER, H.: *Zur Nutzung von Geoidmodellen für die GPS-Höhenbestimmung*. GPS 2002: Antennen, Höhenbestimmungen und RTK-Anwendungen, Beiträge zum 57. DVW-Seminar, Karlsruhe, 16.-17.09.2002, Schriftenreihe des DVW, Band 44, 187-196, Verlag Konrad Wittwer, 2002b.
- DENKER, H.: *Computation of Gravity Gradients Over Europe for Validation/Calibration of GOCE Data*. Proceed. 3rd Meeting of the International Gravity and Geoid Commission, Gravity and Geoid 2002, GG2002, Thessaloniki, Greece, Aug. 26.-30, 2002, <http://olimpia.topo.auth.gr/GG2002/SESSION3/session3.html>
- DENKER, H., PARSELIUNAS, E.: *Evaluation of the European Gravimetric Geoid/Quasigeoid EGG97 over the Lithuanian Territory*. Geodezija ir kartografija (Geodesy and Cartography), Vol XXV, No. 4, 167-173, 1999.
- DENKER, H., TORGE, W., WENZEL, G., IHDE, J., SCHIRMER, U.: *Investigation of Different Methods for the Combination of Gravity and GPS/Levelling Data*. In: SCHWARZ K.-P. (Ed.): Geodesy Beyond 2000 – The Challenges of the First Decade, IAG Symposia, Vol. 121, 137-142, Springer-Verlag, Berlin Heidelberg New York, 2000.
- EBBING, J.: *3-D Dichteverteilung und isostatisches Verhalten der Lithosphäre in den Ostalpen*. Diss., FB Geowissenschaften, FU Berlin, <http://www.diss.fu-berlin.de/2002/192/>
- EBBING, J., BRAITENBERG, C., GÖTZE, H.-J.: *Forward and inverse modeling of gravity revealing insight into crustal structures of the Eastern Alps*. Tectonophysics 337, 191-209, 2001a.
- EBBING, J., BRAITENBERG, C., GÖTZE, H.-J., MEURERS, B.: *The Density Structure of the Eastern Alpine Crust*. Abstract, 5th Workshop of Alpine Geological Studies, Obergurgl (Austria), Geologisch-Paläontologische Mitteilungen 73, Innsbruck, 2001b.
- EBBING, J., GÖTZE, H.-J.: *Preliminary 3D density modeling along the TRANSALP-profile*. Österreichische Beiträge zu Meteorologie und Geophysik, Wien, H. 26, ISSN 1016-6254, 125-136, 2001.
- FESTSCHRIFT TORGE: *Festschrift „Univ.-Prof. em. Dr.-Ing. Wolfgang Torge zum 70. Geburtstag“*. Wiss. Arb. Fachr. Verm.wesen, Univ. Hannover, Nr. 241, Hannover, 2001.
- FLURY, J.: *Schwerefeldfunktionale im Gebirge*. Diss., DGK, C-557, 114 p., München, 2002.
- FLURY, J.: *Local Gravity Field Determination in the Estergebirge (Bavarian Alps)*. In: COLIC, K., MORITZ, H. (Eds.): International Symposium Geodynamics of the Alps-Adria Area by Means of Terrestrial and Satellite Methods, 87-96, Zagreb and Graz, 1999.
- FREEDEN, W.: *Multiscale Modelling of Spaceborne Geodata*. Teubner, Stuttgart, Leipzig, 1999.
- FREEDEN, W.: *A General Construction Principle of Wavelets*. In: BANDAY, A.J., ZARUBI, S., BARTELMANN, M. (Eds.): Proceed. of the MPA/ESO/MPE Workshop 2000 “Mining the Sky”, Garching, 53-70, Springer, 2001a.
- FREEDEN, W.: *Multiscale Modelling of GOCE-DATA-Products*. ESA Proceed. International GOCE User Workshop, ESTEC, Noordwijk, ESA WPP-188, 111-126, 2001b.
- FREEDEN, W., GLOCKNER, O., LITZENBERGER, R.: *Multiscale Modelling From Geopotential Data*. Mathematical Research, Vol. 107, Wiley-VCH, 151-174, 1999a.
- FREEDEN, W., GLOCKNER, O., LITZENBERGER, R.: *A General Hilbert Space Approach to Wavelets and its Application in Geopotential Determination*. Numer. Funct. Anal. Optimiz. 20, 853-879, 1999b.

- FREEDEN, W., HESSE, K.: *On the Multiscale Solution of Satellite Problems by Use of Locally Supported Kernel Functions Corresponding to Equidistributed Data on Spherical Orbits*. *Studia Scientiarum Mathematicarum Hungarica* 39, 37-74, 2002.
- FREEDEN, W., MAIER, T.: *On Multiscale Denoising of Spherical Functions: Basic Theory and Numerical Aspects*. *Electronic Transactions on Numerical Analysis (ETNA)* 14, 40-62, 2002.
- FREEDEN, W., MICHEL, V.: *Constructive Approximation and Numerical Methods in Geodetic Research Today – An Attempt at a Categorization Based on an Uncertainty Principle*. *Journal of Geodesy* 73, 452-465, 1999.
- FREEDEN, W., MICHEL, V.: *Least-squares Geopotential Approximation by Windowed Fourier Transform and Wavelet Transform*. In: KLEES, R., HAAGMANS, R. (Eds.): *Springer Lecture Notes in Earth Sciences* 90, 189-241, 2000.
- FREEDEN, W., MICHEL, V.: *Basic Aspects of Geopotential Field Approximation From Satellite-to-Satellite Tracking Data*. *Math. Meth. Appl. Sci.* 24, 827-846, 2001.
- FREEDEN, W., MICHEL, V., STENGER, M.: *Multiscale Signal-to-Noise Thresholding*. *Acta Geodaetica et Geophysica Hungarica* 36, 55-86, 2001.
- FREEDEN, W., MICHEL, V., NUTZ, H.: *Satellite-to-Satellite Tracking and Satellite Gravity Gradiometry (Advanced Techniques for High-Resolution Geopotential Field Determination)*. *Journal of Engineering Mathematics* 43, 19-56, 2002.
- FREEDEN, W., PEREVERZEV, S.: *Spherical Tikhonov Regularization Wavelets in Satellite Gravity Gradiometry with Random Noise*. *Journal of Geodesy* 74, 730-736, 2001.
- GABRIEL, G., JAHR, T., WEBER, U.: *The gravity field south of the Harz Mountains: Predominated by granitic material?* – *Z. geol. Wiss.* 29 (3), 249-266, 2001.
- GABRIEL, G., PUCHER, R., SCHULZ, R., WONIK, T., WORZYK, P.: *The Tertiary maar near Baruth (Saxony, Germany) – from a hint of a gravity anomaly to a geophysical model*. *International Maar Conference, Daun/Vulkaneifel*, 20.08.-23.08.2000, *Terra Nostra* 2000/6, 138-143, 2000.
- GABRIEL, G., RAPPSILBER, I.: *Der Salzstock Arendsee bei Salzwedel: Ein gravimetrischer Beitrag zur Klärung geologischer Fragestellungen*. *Mitteilungen zur Geologie von Sachsen-Anhalt*. *Mitt. Geol. Sachsen-Anhalt* 5, 5-17, Halle, 1999.
- GIESE, P., ASCH, G., BRASSE, H., GÖTZE, H.-J., KIND, R., WIGGER, P., ARANEDA, M., KAUSEL, E., MARTÍNEZ, E., VIRAMONTE, J.: *Structures and processes in the Central Andes revealed by geophysical investigations*. *Zeitschrift für Angew. Geologie, Sonderheft* 1, 303-309, 2000.
- GLOCKNER, O.: *On Numerical Aspects of Gravitational Field Modelling from SST and SGG by Harmonic Splines and Wavelets (With Application to CHAMP Data)*. PhD thesis, University of Kaiserslautern, Geomathematics Group, Shaker Verlag, Aachen, 2002.
- GOLTZ, G.: *Lokale Schwerefeldbestimmung und -modellierung mit Hilfe der Ableitungen des Schwerepotentials*. Diss., FU Berlin, *Berliner Geowissenschaftliche Abhandlungen, Reihe B*, Bd. 39, 135 p., 2001.
- GÖTZE, H.-J., KRAUSE, S.: *The Central Andean Gravity High, arelic of an old subduction complex?* *Journal of South American Earth Sciences* 14 (8), 799-811, 2002.
- GÖTZE, H.-J., SCHMIDT, S.: *Geophysical 3D Modeling using GIS-Functions*. *Proceed. "8th annual conference of the international association for mathematical geology"*, ISSN 0946-8978, *Terra Nostra*, Heft 04/2002, 87-92, 2002.
- GRAFAREND, E.: *The time-varying gravitational potential field of a massive, deformable body*. *Stud. geoph. et geod.* 44, 364-373, 2000.
- GRAFAREND, E., ARDALAN, A.: *World Geodetic Datum 2000*. *J. Geod.* 73, 611-623, 1999.
- GRAFAREND, E., ARDALAN, A.: *Time evolution of a World Geodetic Datum*. In: ADAM, J., SCHWARZ, K.-P. (Eds.): *Vistas for Geodesy in the New Millennium, IAG Symposia*, Vol. 125, 114-123, Springer-Verlag, Berlin Heidelberg New York, 2002.
- GRAFAREND, E., ARDALAN, A., SIDERIS, M.G.: *The spheroidal fixed-free two-boundary-value problem for geoid determination (the spheroidal Bruns' transform)*. *J. Geod.* 73, 513-533, 1999.
- GRAFAREND, E., AWANGE, J.: *Determination of vertical deflections by GPS/LPS measurements*. *Z.f.Verm.wesen* 125, 279-288, 2000.
- GRAFAREND, E., ENGELS, J., VARGA, P.: *The temporal variation of the spherical and Cartesian multipoles of the gravity field: the generalized MacCullagh representation*. *J. Geod.* 74, 519-530, 2000.
- GRAFAREND, E., HANKE, S.: *The terrain correction in a moving tangent space*. *Stud. geoph. et geod.* 45, 211-234, 2001.
- HAGEDOORN, J.M., WOLF, D., NEUMEYER, J.: *Determination of atmospheric influence on high-accuracy gravity measurements with elastic earth models*. In: SIDERIS, M.G. (Ed.): *Gravity, Geoid and Geodynamics 2000, IAG Symposia*, Vol. 123, 185-191, Springer-Verlag, Berlin Heidelberg New York, 2001.
- HÄHNLE, H., GRAFAREND, E.: *Erstellung eines digitalen Höhenmodells (DHM) mit Dreiecks-Bézier-Flächen*. *Z.f.Verm.wesen* 127, 193-199, 2002.
- HECK, B.: *On the use and abuse of Helmert's second method of condensation*. In: ADAM, J., SCHWARZ, K.-P. (Eds.): *Vistas for Geodesy in the New Millennium, IAG Symposia*, Vol. 125, 144-149, Springer-Verlag, Berlin Heidelberg New York, 2002.
- HEIPKE, C., KOCH, A.: *Qualitätsuntersuchung und Validierung von SRTM ITED-2 Daten in Niedersachsen*. *Abschlussbericht BMBF*, 50EE9927, 97 p., 2002.
- HEIPKE, C., KOCH, A., LOHMANN, P.: *Analysis of SRTM DTM – Methodology and practical results*. *Journal of the Swedish Society for Photogrammetry and Remote Sensing*, 69-80, 2002.
- HESS, D., KELLER, W.: *Gradiometrie mit GRACE Teil I – Fehleranalyse künstlicher Gradiometerdaten*. *Z.f.Verm.wesen* 124, 137-144, 1999a.
- HESS, D., KELLER, W.: *Gradiometrie mit GRACE Teil II – Simulationsstudie*. *Z.f.Verm.wesen* 124, 205-211, 1999b.
- HIRT, C.: *Automatic Determination of Vertical Deflections in Real-Time by Combining GPS and Digital Zenith Camera for Solving the GPS-Height-Problem*. *Proceed. 14th International Technical Meeting of the Institute of Navigation*, 2540-2551, Alexandria, VA, 2001.
- HIRT, C.: *CCD Meets Geodetic Astronomy – The Digital Zenith Camera, a Geodetic State-of-the-art Instrument for Automatic Geographic Positioning in Real-Time*. *Proceed. 12th*

- Meeting of the Astronomical Data Analysis Software and Systems (ADASS) of the Space Telescope Science Institute, published at the Astronomical Society of the Pacific, San Francisco, CA, 2002.
- HIRT, C., BÜRKI, B.: *The Digital Zenith Camera – A New High-Precision and Economic Astrogeodetic Observation System for Real-Time Measurement of Vertical Deflections*. Proceed. 3rd Meeting of the International Gravity and Geoid Commission, Gravity and Geoid 2002, GG2002, Thessaloniki, Greece, Aug. 26-30, 2002.
- HIRT, C., SEEBER, G.: *Astrogeodätische Lotabweichungsbestimmung mit dem digitalen Zenitkameranystem TZK2-D*. Z.f.Verm.wesen 127, 388-396, 2002.
- KNOSPE, S.: *Anwendungen geostatistischer Verfahren in den Geowissenschaften – Fallbeispiele unter Einbeziehung zusätzlicher Fachinformationen*. Diss., TU BA Freiberg, ISBN 3-89820-447-2, Mensch und Buch Verlag, Berlin, 2002.
- KOCH, A., HEIPKE, C., LOHMANN, P.: *Analysis of SRTM DTM – Methodology and practical results*. Proceed. ISPRS Comm. IV Symp., Vol. XXXIV, Part 4, 470-475, Ottawa, July 2002a.
- KOCH, A., HEIPKE, C., LOHMANN, P.: *Bewertung von SRTM Digitalen Geländemodellen – Methodik und Ergebnisse*. Photogrammetrie – Fernerkundung – Geoinformation, 389-398, 2002b.
- KRAWCZYK, C.M., STEIN, E., CHOI, S., OETTINGER, G., SCHUSTER, K., GÖTZE, H.-J., HAAK, V., ONCKEN, O., PRODEHL, C., SCHULZE, A.: *Geophysical constraints on exhumation mechanisms of high-pressure rocks: the Saxo-Thuringian case between Franconian Line and Elbe Zone*. In: FRANKE, ONCKEN, TANNER (Eds.): Special Publication of the Geological Society of London 179, "Orogenic Processes – Quantification and Modelling in the Variscan Belt of Central Europe", Geological Society, London, 303-322, 2000.
- KUDER, J.: *3D Schwerefeldmodellierungen zur Erfassung des tiefen Untergrundes im Nordost-Deutschen Becken*. Diss., FR Geophysik, Fachbereich Geowissenschaften, 116 p., <http://www.diss.fu-berlin.de/2002/139/>
- KUROISHI, Y., DENKER, H.: *Development of Improved Gravity Field Models Around Japan*. In: SIDERIS, M.G. (Ed.): Gravity, Geoid and Geodynamics 2000, IAG Symposia, Vol. 123, 317-322, Springer-Verlag, Berlin Heidelberg New York, 2001a.
- KUROISHI, Y., DENKER, H.: *On the Handling of Ship and Altimetric Gravity Data and the Effect on Local Gravimetric Geoid Models – An Investigation Around Japan*. Proceed. Aropa-Workshop, Institute d'Europe, Münsbach Castle, Luxembourg, Oct. 23-27, 2001b.
- LI, X., GÖTZE, H.-J.: *Ellipsoid, geoid, gravity, geodesy and geophysics – a tutorial*. Geophysics, Vol. 66, No. 6, 1660-1668, 2001.
- LITZENBERGER, R.: *Pyramid Schemes for Harmonic Wavelets in Boundary-Value Problems*. PhD thesis, University of Kaiserslautern, Geomathematics Group, Shaker Verlag, Aachen, 2002.
- MAIER, T.: *Multiscale Geomagnetic Field Modelling From Satellite Data: Theoretical Aspects and Numerical Applications*. PhD thesis, University of Kaiserslautern, Geomathematics Group, Shaker Verlag, Aachen, 2002.
- MAIER, T., MAYER, C.: *Multiscale Downward Continuation of CHAMP FGM-Data for Crustal Field Modelling*. First CHAMP Mission Results for Gravity, Magnetic and Atmospheric Studies, 288- 295, Springer, 2003 .
- MARCHENKO, A.N., BARTHELMES, F., MEYER, U., SCHWINTZER, P.: *Regional Geoid Determination – An Application to Airborne Gravity Data in the Skagerrak*. Scientific Technical Report STR01/07, GFZ Potsdam, 2001.
- MARCHENKO, A.N., BARTHELMES, F., MEYER, U., SCHWINTZER, P.: *Efficient Regional Geoid Computations from Airborne and Surface Gravimetry Data – A Case Study* – In: ADAM, J., SCHWARZ, K.-P. (Eds.): Vistas for Geodesy in the New Millennium, IAG Symposia, Vol. 125, 223-228, Springer-Verlag, Berlin, 2002.
- MENZ, J.: *Forschungsarbeiten im Rahmen des Leibniz-Programms der DFG zur „Markscheiderisch-geologischen Komplexauswertung unter geostatistischen Modellannahmen“ – Aufgabenstellung, Ergebnisse und ihre Bedeutung*. In: MENZ, J. (Ed.): Angewandte Geostatistik in Bergbau, Geologie, Geophysik, Geodäsie und Umweltschutz, Mathematische Geologie, Band 5, 7-21, CPress-Verlag, Dresden, 2000.
- MENZ, J., KNOSPE, S.: *Lokale Bestimmung des Geoids aus terrestrischen Gradiometermessungen unter Nutzung der geostatistischen Integration, Differentiation und Verknüpfung*. Pres. Paper, INTERGEO, Geodätische Woche, Session 8, Geodätische Datenanalyse, Geostatistik, Mathematische Statistik, Validierung, Qualitätsanalyse, GIS, diskrete Modelle, Köln, 21.09.2001.
- MENZ, J., KNOSPE, S.: *Lokale Bestimmung des Geoids aus terrestrischen Gradiometermessungen unter Nutzung geostatistischer Methoden*. Z.f.Verm.wesen 127, 321-332, Wießner-Verlag, Augsburg, 2002.
- MICHEL, V.: *A Multiscale Method for the Gravimetry Problem: Theoretical and Numerical Aspects of Harmonic and Anharmonic Modelling*. PhD thesis, University of Kaiserslautern, Geomathematics Group, Shaker Verlag, Aachen, 1999.
- NOVAK, P., HECK, B.: *Downward continuation and geoid determination based on band-limited airborne gravity data*. J. Geod. 76, 269-278, 2002.
- NOVAK, P., KERN, M., SCHWARZ, K.P., HECK, B.: *The determination of the geoid from airborne gravity data*. UCGE Reports, No. 30013, Dept. of Geomatics Engineering, Univ. of Calgary, 222 p., Calgary, Canada, 2001.
- NUTZ, H.: *A Unified Setup of Gravitational Field Observables*. PhD thesis, University of Kaiserslautern, Geomathematics Group, Shaker Verlag, Aachen, 2002.
- OMARINI, R., GÖTZE, H.-J., SUREDA, R.J., SEILACHER, A., PFLÜGER, F.: *Puncoviscana folded belt in NW Argentina: testimony of Late Proterozoic Rodinia fragmentation and pre-Gondwana collisional episodes: a reply*. International Journal of Earth Sciences (Geol. Rundschau), Vol. 90, 894-902, 2001.
- OTT, N., GÖTZE, H.-J., SCHMIDT, S., BURGER, H., ALTEN, M.: *Meta Geo-information System Facilitates Use of Complex Data for Study of Central Andes*. EOS, Vol. 83, No. 34, http://www.agu.org/eos_elec/020081e.html, 2002.
- SCHÄFER, C., GRAFAREND, E.: *On the determination of gravitational information from GPS-tracked satellite missions*. Artificial Satellites, J. Planetary Geod. 37, 31-49, 2002.

- SCHÄFER, U.: *Towards the unification of European height systems using analytical models of the Earth's Gravity Field*. In: SCHÄFER, U. (Ed.): Proceed. AROPA Workshop, Luxembourg, Cahiers of ECGS, Vol. 20, Oct 23-27, 2001.
- SCHÄFER, U., STRAKHOV, V.N., STRAKHOV, A.V.: *New Linear Approximations of the Earth's Gravity Field: Theoretical Basis And Practical Applications*. In: SCHÄFER, U. (Ed.): Proceed. AROPA Workshop, Luxembourg, Cahiers of ECGS, Vol. 20, Oct 23-27, 2001.
- SCHMIDT-AURSCH, M.C.: *Die Krustenstruktur der Fjordregion Ostgrönlands zwischen dem präkambrischen Schild und den rezenten mittelozeanischen Rücken: Ergebnisse seismischer und gravimetrischer Modellierungen*. Diss., Fachbereich 5 (Geowissenschaften), Universität Bremen, 2002.
- SCHÖBEL, R., HEIN, G.W., EISSFELLER, B.: *Renaissance of astrogeodetic levelling using GPS/CCD zenith camera*. IAIN World Congress, U.S. ION Annual Meeting Receipt, San Diego, Calif., U.S.A., June 26-28, 2000.
- STRAKHOV, V.N., SCHÄFER, U., STRAKHOV, A.V.: *SNAP Models of the Regional Gravitational Field in Central Europe*. Basic Problems of the Theory of Interpretation of Gravimetric and Magnetic Anomalies, Russian Acad. of Sciences, United Institute of Physics of the Earth, 168-182, Moscow, 1999a.
- STRAKHOV, V.N., SCHÄFER, U., STRAKHOV, A.V.: *New linear approximations of elements of the gravitational field of the Earth in global and in regional variants (in Russian)*. Proceed. Conference "Geophysics and Mathematics", 212-222, Moscow, Nov 22-26, 1999b.
- STRAKHOV, V.N., SCHÄFER, U., STRAKHOV, A.V.: *New linear approximation of the gravitational field of the Earth (in Russian)*. Basic Problems of the Theory of Interpretation of Gravimetric and Magnetic Anomalies, Russian Acad. of Sciences, United Institute of Physics of the Earth, 126-167, Moscow, 1999c.
- STRAKHOV, V.N., SCHÄFER, U., STRAKHOV, A.V.: *Improved analytical approximations of the Earth's gravitational field*. In: SCHWARZ K.-P. (Ed.): Geodesy Beyond 2000 – The Challenges of the First Decade, IAG Symposia, Vol. 121, 196-201, Springer-Verlag, Berlin Heidelberg New York, 2000.
- STRAKHOV, V.N., SCHÄFER, U., STRAKHOV, A.V., OPPITZ, K.: *On a new paradigm of gravimetry (in Russian)*. Questions of theory and practice of geological interpretation of gravitational, magnetic and electrical fields, Russian Acad. of Sciences, United Institute of Physics of the Earth, 125-128, Moscow, 2001.
- TORGE, W.: *Gravimetry*: Russische Übersetzung, Mir, Moskau, 1999.
- TORGE, W.: *Geodesy, 2nd Edition, Griechische Übersetzung*, N.T.U.A. Press, Athens, 2000.
- TORGE, W.: *Geodesy*. 3rd completely revised and extended edition, W. de Gruyter, Berlin-New York, 2001.
- TORGE, W.: *Geodäsie*. 2. Vollständig überarbeitete und erweiterte Auflage, W. de Gruyter, Berlin-New York, 2002.
- TORGE, W., DENKER, H.: *Zur Verwendung des Europäischen Gravimetrischen Quasigeoids EGG97 in Deutschland*. Z.f.Verm.wesen 124, 154-166, 1999.
- TSOULIS, D.: *Analytical and numerical methods in gravity field modelling of ideal and real masses*. Deutsche Geodätische Kommission bei der Bayerischen Akademie der Wissenschaften, Reihe C – Dissertationen, Heft Nr. 510, München, 1999a.
- TSOULIS, D.: *Multipole expressions for the gravitational field of some finite bodies*. Bollettino di Geodesia e Scienze Affini, No. 4, 353-381, 1999b.
- TSOULIS, D.: *A note on the gravitational field of the right rectangular prism*. Bollettino di Geodesia e Scienze Affini, No. 1, 21-35, 2000.
- TSOULIS, D.: *Terrain correction computations for a densely sampled DTM in the Bavarian Alps*. Journal of Geodesy 75 (5/6), 291-307, 2001.
- TSOULIS, D., PETROVIC, S.: *On the singularities of the gravity field of a homogeneous polyhedral body*. Geophysics 66 (2), 535-539, 2001.
- WENZEL, G.: *Schwerefeldmodellierung durch ultra-hochauflösende Kugelfunktionsmodelle*. Z.f.Verm.wesen 124, 144-154, 1999.
- WIEDERHOLD, H., AGSTER, G., GABRIEL, G., KIRSCH, R., SCHENCK, P.-F., SCHEER, W., VOSS, W.: *Geophysikalische Erkundung quartärer Grundwasserleiter im südlichen Schleswig*. Z. angew. Geol. 48, 13-26, 2002a.
- WIEDERHOLD, H., GABRIEL, G., KIRSCH, R., SIEMON, B., VOSS, W.: *Geophysical investigation of Pleistocene valleys*. In: KIRSCH, R. (Ed.): Proceedings of the Workshop „Buried valleys – water resources for the future“, 28.09.2001, Flintbek, 2002b.
- WIEDERHOLD, H., GABRIEL, G., KIRSCH, R., SIEMON, B., VOSS, W.: *Geophysical investigation of pleistocene valleys*. 7th Meeting Environmental and Engineering Geophysics, 2.-6. September 2001, Birmingham/UK, EEGS2001 Proceedings, 212-213, 2001.
- WITTKOPF, V.: *Analyse und Formalisierung geophysikalisch-geologischen Wissens am Beispiel der integrierten Interpretation krustaler Strukturen*. Diss., FU Berlin, Berliner Geowissenschaftliche Abhandlungen, Reihe B, Bd. 40, 107 p., 2002.

SECTION IV

GENERAL THEORY AND METHODOLOGY

General Theory and Methodology

– Overview and highlights –

B. HECK¹

According to the IAG by-laws and the terms of reference, section IV in the hitherto existing structure of the IAG covers general aspects of geodetic theory and methodology. Its scope has not been confined to a specific topic like in the other sections, but rather all topics have been shared more or less with other IAG sections, with the accent pointing towards a systematic treatment of the respective problems on a mathematical and physical basis. The basic structure of Section IV, consisting of Special Commission SC 1 and the Special Study Groups, has been retained in the period 1991 – 2003. In the past period, the scientific work in Section IV mainly has been performed in the following sub-structure bodies:

SC 1: *Mathematical and Physical Foundations of Geodesy* (President: P. HOLOTA, Czech Rep.)

Subcomm. 1: *Statistics and Optimization* (Chair: PEILIANG XU, Japan)

Working group: *Spatial Statistics for geodetic Science* (Chair: B. SCHAFFRIN, USA)

Subcomm. 2: *Numerical and Approximation Methods* (Chair: W. FREEDEN, Germany)

Subcomm. 3: *Boundary Value Problems* (Chair: R. LEHMANN, Germany)

Subcomm. 4: *Geometry, Relativity, Cartography, GIS* (Chair: V. SCHWARZE, Germany)

Subcomm. 5: *Hydrostatic/isostatic Earth Reference Models* (Chair: A. N. MARCHENKO, Ukraine)

SSG 4.187: *Wavelets in Geodesy and Geodynamics* (Chair: W. KELLER, Germany)

SSG 4.188: *Mass Density from Joint Inverse Gravity Modelling* (Chair: G. STRYKOWSKI, Denmark)

SSG 4.189: *Dynamic Theories of Deformation and Gravity Field* (Chair: D. WOLF, Germany)

SSG 4.190: *Non-Probabilistic Assessment in Geodetic Data Analysis* (Chair: H. J. KUTTERER, Germany)

SSG 4.191: *Theory of Fundamental Height Systems* (Chair: C. JEKEL, USA)

SSG 4.195: *Fractal Geometry in Geodesy* (Chair: E. GRAFAREND, Germany)

The strong representation of German scientists in the work of IAG Section IV can easily be recognized from the origin of the chair persons 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 in international symposia, national meetings and SSG workshops. For IAG Section IV the IAG Scientific Assembly which took place on Sept. 3-7, 2001 in Budapest/Hungary had an eminent importance, together with the 5th Hotine-Marussi Symposium (July 10-14, 2002 in Matera/Italy) in the series of the traditional Section IV Symposia. Furthermore, the International Symposium on Gravity, Geoid and Geodynamics (July 31-Aug. 4, 2000 in Banff/Canada), the IAG Symposium on Vertical Reference Systems (Feb. 21-23 in Cartagena/Columbia), the 1st International Symposium on Robust Statistics and Fuzzy Techniques in Geodesy and GIS (March 12-16, 2001 in Zurich/Switzerland, organized by SSG 4.190), and the W. A. Heiskanen Symposium in Geodesy (Oct. 1-5, 2002 in Columbus/Ohio, USA) have to be mentioned, where significant contributions by German geodesists have been made in the field of IAG Section IV. On the national basis, the series of annual meetings *Geodätische Woche (Geodetic Week)* has been continued (1999 Hannover, 2000 Berlin, 2001 Cologne, 2002 Frankfurt); these workshops, organized as a part of the annual INTERGEO, in particular addressed young researchers in Geodesy.

Geodetic theory and methodology is also reflected in a number of textbooks published in the past 4-years period by German authors: In 1999 W. FREEDEN published the text book *Multiscale Modelling of Spaceborne Geodata* (Teubner, Stuttgart/Leipzig). K. R. KOCH presented the 2nd edition of *Parameter estimation and Hypothesis Testing in Linear Models* (Springer, 1999) as well as *Einführung in die Bayes-Statistik (Introduction to Bayesian Statistics)*, Springer, 2000). The theory and applications of adjustment computation has been treated by W. NIEMEIER in the textbook on *Ausgleichsrechnung (Least Squares Adjustment)*, W. de Gruyter, Berlin/New York, 2002), while the theory of geodetic reference frames has been presented by A. SCHÖDLBAUER in *Geodätische Astronomie (Geodetic Astronomy)*, W. de Gruyter, Berlin/New York, 2000). Furthermore, W. TORGE has completely revised and extended his wide-spread textbook *Geodesy* (3rd edition in English, 2001; 2nd edition in German, 2003, both W. de Gruyter, Berlin/New York),

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and G. SEEBER has completed the 2nd edition of *Satellitengeodäsie (Satellite Geodesy)*, W. de Gruyter, Berlin/New York, 2003). Finally the volume of review papers edited by E. GRAFAREND, W. KRUMM, V. S. SCHWARZE *Geodesy – The Challenge of the 3rd Millenium* (Springer 2002) should be mentioned.

The following contributions on Physical Aspects of Geodetic Modelling, Mathematical Aspects of Geodetic Modelling, Stochastic Methods of Data Evaluation, and Non-Stochastic Methods of Data Evaluation provide details on the work related to IAG Section IV which was carried out in Germany in the period 1999-2003.

The physical aspects of modelling in Geodesy are related to the basic theories of Physics (Newtonian mechanics, theory of relativity, quantum theory) forming in some way the background of any modelling of geodetic observations. Significant advances in the past four-year period are visible in the theory of fundamental reference frames and height systems, in methods for the description of the Earth's space- and time-variable gravity field and deformation, and in modelling the propagation of electromagnetic signals in refractive media; advanced models in these field have become necessary due to the rapid development in the quality and availability of space geodetic observations. Another challenging task related to physical modelling is induced by the fact that Geodesy has to provide a consistent set of fundamental parameters and constants which also fits the demands of Geophysics and Astronomy. With respect to the structure of IAG Section IV reference is made to sub-commissions 4 and 5 of Special Commission 1, to Special Commission 3 (Fundamental Parameters), and to Special Study Groups 4.189, 4.191, and 4.195.

The mathematical aspects of geodetic modelling refer to new developments in numerical mathematics and digital signal processing, including advanced tools such as wavelet

analysis in one and two dimensions; applications in Geodesy range from time series analysis (e.g. polar motion) to feature extraction and data compression. Special emphasis has also been put into the formulation and solution of boundary value problems as well as inverse and improperly posed problems, related e.g. to downward continuation. Furthermore, applications of differential geometry to different fields of Geodesy have to be mentioned. Mathematical aspects of modelling have been studied by sub-commissions 2, 3 and 4 of Special Commission 1 as well as by the Special Study Groups 4.187 and 4.188.

Since the foundations of least squares adjustment by C. F. Gauß stochastic methods of data evaluation have played a dominant role in Geodesy, in particular in the framework of quality analysis. Strong progress has been made in the adaption of statistical inference – including Bayesian statistics – to the fields of Geodesy and Surveying, digital Photogrammetry and image processing, and digital topography and cartography. Other topics belonging to this subject are stochastic signal analysis and geostatistics. These topics have been addressed to by the subcommission 1 of Special Commission 1.

Traditionally and methodologically, a distinction is made between deterministic and stochastic signals in geodetic observations. More and more, deterministic signal analysis makes use of wavelet transforms instead of the classical Fourier techniques. Recently, the spectrum of uncertainty in geodetic data and models has been extended from the purely random status; non-random uncertainty of the data can be taken into account using interval mathematics, fuzzy data analysis and artificial neural networks. Studies in this respect have been embedded in sub-commission 2 of Special Commission 1 and in Special Study Group 4.190.

Physical aspects of geodetic modelling

E. W. GRAFAREND¹

With reference to the International Association of Geodesy (IAG) bodies let us report on National Activities in the range of

- Special Commission #1
Mathematical and Physical Foundations of Geodesy
(Chairman: P. Holota, Czech Republic)
- Special Commission #3
Fundamental Constants
(Chairman: E. Groten, Germany)
- Special Study Group 4.189
Dynamic Theories of Deformation and Gravity Field
(Chairman: D. Wolf, Germany)
- Special Study Group 4.191
Theory of Fundamental Height Systems
(Chairman: C. Jekeli, USA)
- Special Study Group 4.195
Fractal Geometry in Geodesy
(Chairman: E. Grafarend, Germany)

Fundamental reference frames

The papers by MÜLLER (1999, 2000, 2001), MÜLLER et al. (1999a, 1999b, 2000, 2002) and MÜLLER and TESMER (2002) work on varying objectives of analyses of LLR data in order to provide sets of station coordinates and Earth Orientation parameters for the annual realizations of the IERS2000. Included is an overview over the prospects of LLR today and its impact for Geodesy and Relativity.

Theory of the Earth's gravity field and deformation

In ALBERTELLA et al. (1999) the Slepian problem is extended to and solved for the sphere; band-limited functions on a bounded spherical domain are developed in order to derive a natural solution for the polar gap problem in satellite geodesy and to extract the maximum amount of information from non-polar gravity field missions. BIANCALE et al. (2000) present a new model of the Earth's gravity field, called GRIM5-S1, which is a result of a joint German-French co-operation. The solution is based on satellite orbit perturbation analysis and exploits tracking data from 21 satellites to solve simultaneously for the gravitational and ocean tide potential and tracking station positions. REIGBER et al. (2002) compute a new long-wavelength global gravity field model, called EIGEN-1S, using three months of GPS satellite-to-satellite tracking and accelerometer data of the CHAMP satellite mission. The solution is derived solely from analysis of satellite orbit perturbations, i.e. it is independent of oceanic

and continental surface gravity data. The publication by HECK (2002) generalizes Helmert's methods of condensation, considering a variable depth of the condensation layer below the geoid. Expressing the respective formulae for the combined topographic-condensation reduction both in space and frequency domain for a spherical approximation of the Earth, some drawbacks of Helmert's second method of condensation become visible. KABAN and SCHWINTZER (2001) use isotropic shear-wave velocities from the Ekström/Dziewinski S20 global tomographic model and residual 'crustfree' gravity to determine by inversion density-velocity relations for different mantle layers. KABAN et al. (1999) derive a global isostatic gravity model of the Earth. MARCHENKO et al. (2002) perform a study on how to compute efficiently stable regional geoids from airborne and surface gravimetry data. NOVAK et al. (2001) modify the theory for the determination of the gravimetric geoid for the application of airborne gravimetry, i.e. for gravity observed from a low altitude-flying aircraft. The downward continuation of the harmonic disturbing gravity potential, derived at flight level from discrete observations of airborne gravity by the spherical Hotine integral, to the geoid is discussed in NOVAK and HECK (2002). SNEEUW (2000) presents a semi-analytical approach to gravity field determination from space-borne observations on the basis of the lumped coefficient formulation, linking gravity field functionals to the unknown gravity field. MARCHENKO and SCHWINTZER (2002) estimate the dynamic figure of the Earth as characterized by the principal axes and principal moments of inertia from satellite-derived gravitational harmonic coefficients of second degree in recent global Earth gravity models and from the dynamical ellipticity resulting from the precession constant observed by VLBI. SCHMIDT and SHUM (2003) treat the multi-resolution representation of the gravity field using spherical wavelets. SCHMIDT et al. (2002) describe a general scheme for the calculation of both the spherical wavelet coefficients for a space- and frequency-dependent representation of gravity data and the computation of local geoid undulations by means of the inverse spherical wavelet transform. The processes of sea level changes and isostatic compensation are the subject of the paper by BÖLLING et al. (2001) who examine and verify the processes using iceload induced vertical movements and geoid changes under the assumption of viscoelastic Earth models. BÜRGER et al. (2002) describe temporal gravity changes and glacial-isostatic compensation movements near the shrinking Vatnajökull ice shield in SE Iceland. GÖBELL et al. (1999) work on load-induced disturbances for a maximum of three-layered, self-gravitating, spherical Earth models and different rheologies. HAGEDOORN

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et al. (2001a,b) model and calculate the total contribution of the atmosphere to incremental gravity with the intention to perform reductions on high precision gravity measurements being registered with a super-conducting gravimeter located at GFZ Potsdam. KAUFMANN and WOLF (1999) consider load-induced viscoelastic and viscous perturbations of incompressible and vertically homogeneous flat Earth models with lateral variations of the shear modulus and viscosity. KLEMANN and WOLF (1999) investigate the implications of a ductile crustal layer for the interpretation of glacial-isostatic adjustment using a layered, incompressible Maxwell viscoelastic Earth model and a simplified representation of the Fennoscandian glaciation. MARTINEC (2002) computes a semi-analytical solution for 2D forward modelling of viscoelastic relaxation in a spherical Earth model with a nested axisymmetric craton and MARTINEC et al. (2001a) test the impact of lateral viscosity variations in the top 200 km of the mantle on the interpretation of Fennoscandian postglacial uplift data in terms of 1D viscosity models. In MARTINEC et al. (2001b) an analytical form of the layer propagator matrix for the response of a locally incompressible, layered, linear-viscoelastic sphere to an external load under the assumption that the initial density stratification within each layer is parametrized by Darwin's law, is presented. The contribution by MARTINEC and WOLF (1999) describes a semi-analytical solution to the 2-D forward modelling of viscoelastic relaxation in a heterogeneous model consisting of eccentrically nested spheres. THOMA and WOLF (1999) simulate the effects of Fennoscandian postglacial rebound, temporal gravity change and isostatic compensation using a combination of a planar, incompressible, viscoelastic and lateral homogeneous Earth model with a load model consisting of circular shaped discs. THOMA and WOLF (2001) use a compressible, self-gravitating, spherical Earth model with Maxwell viscoelasticity and a load model parabolic in cross section and elliptic in plan view to interpret the observations performed near the Vatnajökull ice cap in SE Iceland in terms of viscosity stratification. The study by WOLF and KAUFMANN (2000) is concerned with load-induced Maxwell viscoelastic perturbations of a half-space with a compressional and compositional initial density gradient. Analytic solutions to this problem are deduced for the limiting cases of purely compressional and purely compositional stratification. WOLF (2002) considers a compositionally and entropically stratified, compressible, rotating fluid Earth and studies gravitational-viscoelastic perturbations of its hydrostatic initial state. WOLF and LI (2002) give an analytical solution for load-induced perturbations of a spherical, compressible Earth model consisting of a viscoelastic mantle and an inviscid core. Density stratification in the mantle is assumed to conform to Darwin's law. WIECZERKOWSKI et al. (1999) outline a new method for estimating a relaxation-time spectrum from a set of strandline data, which is based on a damped least-squares solution for spherical harmonic coefficients associated with the strandline heights. In order to analyse the geometry of a geodetic network and its variation in time MUSOYKA (1999) extends the model of three-dimensional integrated geodesy to four-dimensional

geodesy by considering the temporal variation of the network points both in space and time.

Fundamental height systems

The paper by RUMMEL (2002) deals with the problem of the global unification of height systems and GOCE, and discusses alternative methods for the unification. In RUMMEL and HECK (2001) some critical remarks on the definition and realization of the EVRS are formulated.

Fundamental constants

In BURSA et al. (2001) TOPEX/POSEIDON satellite altimeter data are used for investigating the long-term variations of the geoidal geopotential W_0 and the geopotential scale factor $R_0=GM/W_0$, with GM being the adopted geocentric gravitational constant. The paper by GROTEN (2003) summarizes the implication and importance of fundamental constants and attempts to describe their role in future systems.

References

- ALBERTELLA A., SANZO F., SNEEUW N. (1999): *Band-limited functions on a bounded spherical domain: the Slepian problem on the sphere*, Journal of Geodesy 73 (1999) 436-447
- BIANCALE R., BALMINO G., LEMOINE J.-M., MARTY J.-C., MOYNOT B., BARLIER F., EXERTIER P., LAURAIN O., GEGOUT P., SCHWINTZER P., REIGBER CH., BODE A., KÖNIG R., MASSMANN F.-H., REIMONDO J.C., SCHMIDT R., ZHU S.Y. (2000): *A new global Earth's gravity field model from satellite orbit perturbations*. Geophysical Research Letters 27 (2000) 3611-3614
- BÖLLING K., HAGEDOORN J., WOLF D., GRAFAREND E.W. (2001): *Berechnung eislaminduzierter Vertikalbewegungen und Geoidänderungen in Südostalaska mit Hilfe viskoelastischer Erdmodelle*. GeoForschungsZentrum Potsdam, STR01/08, Scientific Technical Report 2001, 47 p.
- BÜRGER ST., JACOBY W.R., HAGEDOORN J., WOLF D. (2002): *Zeitliche Schwereänderung und glazio-isostatische Ausgleichsbewegung am Vatnajökull, Südost-Island*. Mitteilungen der Deutschen Geophysikalischen Gesellschaft 1 (2002), 2-10
- BURSA M., GROTEN E., KENYON S., KOUBA J., RADEJ K., VATRT V., VOJTISKOVA M. (2001): *Earth's dimension specified by geoidal geopotential*. Presented at the IAG 2001 Scientific Assembly, Sep 2-7, 2001, Budapest, Hungary
- GÖBELL S., THOMA M., WOLF D., GRAFAREND E.W. (1999): *Berechnung auflastinduzierter Horizontalverschiebungen, Geoidhöhen und Freiluft-Schwereanomalien für ein selbstgravitierendes, sphärisches Erdmodell und unterschiedliche Rheologien*. GeoForschungsZentrum Potsdam, STR99/24, Scientific Technical Report, 76p, Potsdam 1999
- GROTEN E. (2003): *Fundamental constants and their implications*. Paper presented at the IUGG – General Assembly, 30 June until 14 July 2003, Sapporo, Japan.
- HAGEDOORN J.M., WOLF D., NEUMEYER J. (2001a): *Modellierung von atmosphärischen Einflüssen auf hochgenaue Schweremessungen mit Hilfe elastischer Erdmodelle*.

- GeoForschungsZentrum Potsdam, STR00/15, Scientific Technical Report, Potsdam 2001
- HAGEDOORN M.J., WOLF D., NEUMEYER J. (2001b): *Determination of atmospheric influence on high-accuracy gravity measurements with elastic Earth models*. In: Sideris, M.G. (Ed.), Gravity, Geoid, and Geodesy 2000, International Association of Geodesy Symposia, 123, 185-192, Springer Verlag, Berlin 2001
- HECK B. (2002): *On the use and abuse of Helmert's second method of condensation*. In: Adam J., Schwarz K.P., Vistas for Geodesy in the New Millenium, IAG 2001 Scientific Assembly, Sept. 2001. IAG Symposia 125 (2002) 144-149, Springer
- KABAN M.K., SCHWINTZER P. (2001): *Oceanic upper mantle structure from experimental scaling of V_s and density at different depths*. Geophysical Journal International 147 (2001) 199-214
- KABAN M.K., SCHWINTZER P., TIKHOTSKY S.A. (1999): *A global isostatic gravity model of the Earth*. Geophysical Journal International 136 (1999) 519-536
- KAUFMANN G., WOLF D. (1999): *Effects of lateral viscosity variations on postglacial rebound: an analytical approach*. Geophysical Journal International 137 (1999) 489-500
- KLEMANN V., WOLF D. (1999): *Implications of a ductile crustal layer for the deformation caused by the Fennoscandian ice sheet*. Geophysical Journal International 139 (1999) 216-226
- MARCHENKO A.N., BARTHELMES F., MEYER U., SCHWINTZER P. (2002): *Efficient regional geoid computations from airborne and surface gravimetry data – a case study*. In: Adam, Schwarz (eds.): Vistas for Geodesy in the New Millenium. International Association of Geodesy symposia, Symposium no. 125, 223-228, Springer Berlin 2002
- MARCHENKO A.N., SCHWINTZER P. (2002): *Principal axes and principal moments of inertia from recent satellite gravity field solutions*. In: Adam, Schwarz (eds.): Vistas for Geodesy in the New Millenium. International Association of Geodesy symposia, Symposium no. 125, 138-143, Springer Berlin 2002
- MARTINEC Z. (2002): *Semi-analytical solution for the viscoelastic relaxation in spherical Earth with an axisymmetric craton*. Acta Geodaetica et Geophysica Hungarica 37 (2002) 61-78
- MARTINEC Z., CADEK O., FLEITOUT L. (2001a): *Can the 1D viscosity profiles inferred from postglacial rebound data be affected by lateral viscosity variations in the tectonosphere?* Geophysical Research Letters 28 (2001) 4403-4406
- MARTINEC Z., THOMA M., WOLF D. (2001b): *Material versus local incompressibility and its influence on glacial-isostatic adjustment*. Geophysical Journal International 144 (2001) 136-156
- MARTINEC Z., WOLF D. (1999): *Gravitational-viscoelastic relaxation of eccentrically nested spheres*. Geophysical Journal International 138 (1999) 45-66
- MÜLLER J. (1999): *Zeitskalen*. In: 3. DFG-Rundgespräch zum Thema Bezugssysteme, Wettzell, April 1998, Mitteilungen des BKG, ed. by M.Schneider, 5 (1999) 77-83
- MÜLLER J. (2000): *FESG/TUM, Report about the LLR Activities*. ILRS Annual Report 1999, M.Pearlman and L.Taggart (eds.), P. 204-208, 2000
- MÜLLER J. (2001): *FESG/TUM, Report about the LLR Activities*. ILRS Annual Report 2000, M.Pearlman, M.Torrence, L.Taggart (eds.), pp. 7-35 – 7-36, 2001.
- MÜLLER J., CHAPRONT J., RIES J.G., WILLIAMS J. (2002): *LLR and Tidal Effects*. Bulletin D'Informations Marées Terrestres (BIM), ed. by B.Ducarme, 134 (2002) 10553-10557
- MÜLLER J., EGGER D., REICHHOFF B., SCHNEIDER M., SCHREIBER U. (2000): *Lunar Laser Ranging at its Best*. In: Towards an Integrated Global Geodetic Observing System (IGGOS), Proceedings of the IAG Section II Symposium, held in Munich, Germany, Oct. 1998, IAG Symposia, Vol. 120, pp. 161-164, Springer Verlag, 2000
- MÜLLER J., NORDTVEDT K., SCHNEIDER M., VOKROUHLICKY D. (1999a): *Improved determination of relativistic quantities from LLR*. In: Proceedings of the 11th Workshop on Laser Ranging Instrumentation, Deggendorf, Sept. 1998, Mitteilungen des Bundesamtes für Kartographie und Geodäsie, Band 10, pp. 216-222, Frankfurt 1999
- MÜLLER J., NORDTVEDT K., SCHNEIDER M., VOKROUHLICKY D. (1999b): *What can LLR provide to Relativity?*. In: Proceedings of the 8th Marcel Grossmann Meeting on General Relativity, Jerusalem, Israel, June 1997, ed. by T.Piran, P. 114-121, World Scientific, 1999.
- MÜLLER J., TESMER V. (2002): *Investigation of Tidal Effects in Lunar Laser Ranging*. Journal of Geodesy 76 (2002) 232-237
- MUSOYKA S. (1999): *A model for a four-dimensional integrated regional geodetic network*. Dissertation TH Karlsruhe, 1999
- NOVAK P., HECK B. (2002): *Downward continuation and geoid determination based on band-limited airborne gravity data*. Journal of Geodesy 76 (2002) 269-278
- NOVAK P., KERN M., SCHWARZ K.-P., HECK B. (2001): *The determination of the geoid from airborne gravity data*. UCGE Reports no. 30013, Dept. of Geomatics Engineering University of Calgary, Calgary/Canada, 2001
- REIGBER CH., BALMINO G., SCHWINTZER P., BIANCALE R., BODE A., LEMOINE J.-M., KÖNIG R., LOYER S., NEUMAYER H., MARTY J.-C., BARTHELMES F., PEROSANZ F., ZHU S.Y. (2002): *A high quality global gravity field model from CHAMP GPS tracking data and accelerometry (EIGEN-IS)*. Geophysical Research Letters 29 (14) (2002)
- RUMMEL R. (2002): *Global unification of height systems and GOCE, gravity, geoid and geodynamcis 2000*. Sideris M.G. (ed.), IAG Symposia 123 (2002) 13-20, Springer Heidelberg
- RUMMEL R., HECK B. (2001): *Some critical remarks on the definition and realization of the EVRS*. In: Torres J.A., Hornik H. (eds.): Reports on the Symposium of the IAG Subcommittee for Europe, Commission X, held in Tromsø, June 2000. Veröffentlichung der Bayerischen Kommission für die Internationale Erdmessung, Astrogeodätische Arbeiten, Heft Nr. 61 (2001) 114-115
- SCHMIDT M., MARTINEZ W., FLOREZ J. (2002): *General scheme for the computation of regional geoid undulations using spherical wavelets*. In: Vertical Reference Systems, Springer 2002, IAG Symposia 124 (2002) 209-214
- SCHMIDT M., SHUM C.K. (2003): *Multi-resolution representation of the gravity field using spherical wavelets*. In: Proceedings of the Weikko A. Heiskanen Symposium in Geodesy,

- Columbus/OH, 1-4 October 2002, ed. by C. Jekeli, p. 48, 2003.
- SNEEUW N. (2000): *A semi-analytical approach to gravity field analysis from satellite observations*, Deutsche Geodätische Kommission, Reihe C, Nr. 527, München 2000
- THOMA M., WOLF D. (1999): *Bestimmung der Mantelviskosität aus Beobachtungen der Landhebung und Schwere in Fennoskandien*. GeoForschungsZentrum Potsdam, STR99/02, Scientific Technical Report, Potsdam 1999
- THOMA M., WOLF D. (2001): *Inverting land uplift near Vatnajökull, Iceland, in terms of lithosphere thickness and viscosity stratification*. In: Sideris, M.G. (Ed.), *Gravity, Geoid, and Geodynamics 2000*, International Association of Geodesy Symposia, 123, 97-102, Springer-Verlag, Berlin 2001
- WIECZERKOWSKI K., MITROVICA J. X., WOLF D. (1999): *A revised relaxation-time spectrum for Fennoscandia*. *Geophysical Journal International* 139 (1999) 69-86
- WOLF D. (2002): *Gravitational viscoelastodynamics*. *Acta Geodaetica et Geophysica Hungarica* 37 (2002) 29-60
- WOLF D., KAUFMANN G. (2000): *Effects due to compressional and compositional density stratification on load-induced Maxwell-viscoelastic perturbations*. *Geophysical Journal International* 140 (2000) 51-62
- WOLF D., LI G. (2002): *Compressible viscoelastic Earth models based on Darwin's law*. In: Mitrovica, J.X.; Vermeersen, L.L.A. (Ed.), *Ice Sheets, Sea Level and the Dynamic Earth*, *Geodynamics Series*, American Geophysical Union, Washington, D.C. 29 (2002) 275-292

Mathematical aspects of geodetic modelling

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Introduction

Due to the technological progress in space- and communication technique a number of new observation methods, generating new data types came into the view of geodetic applications. In order to exploit all information contained in this data it is necessary to refine the mathematical models, connecting the observations with the processes to be studied. Here geodesy took advantage from new developments in numerical mathematics and digital signal processing. One of these developments is the wavelet transformation, which enhances the classical Fourier transformation by the ability to locate signal parts not only in the frequency but simultaneously in the time domain.

But besides these new techniques more traditional methods like differential geometry found new applications in the field of geodesy and cartography.

In the period of 1999 to the beginning of 2003 considerable theoretical and practical work has been done by different researchers. This contribution is to summarize the German advances and developments made during this period.

Differential geometry /math. cartography

The use of differential geometric techniques for the solution of geodetic and cartographic problems has a longstanding tradition. While this topic flourished in the seventieth, presently other subjects came into the focus of interest.

Nevertheless, there is still a continuous progress in the application of differential geometric methods to geodesy. In the period, which is covered in this report, German contributions to the application of differential geometry solely came from the University Stuttgart. These contributions deal with the construction of Gaussian surface normal coordinates on different surfaces (GRAFAREND 2000, GRAFAREND 2001). The construction principle is the minimum distance mapping which leads to closed formulae for the conversion of Cartesian and surface normal coordinates into each other. These closed formulae take advantage of the Buchberger algorithm for the solution of polynomial equations.

Another differential geometric application is the direct transformation of local conformal coordinates to global conformal coordinates without the need of additional height information (GRAFAREND et al. 2000).

Besides the application of the differential geometric description of surfaces also the differential geometric description

of curves is exploited. In (GRAFAREND 2002a) a new series expansion of the Fresnel integral for the construction of a clothoid is presented. (GRAFAREND 2002b) deals with the minimal-distance mapping of a point outside the clothoid to this special curve.

Besides these terrestrial applications of differential geometry the paper (AUSTEN and GRAFAREND 2001) is a contribution of differential geometry to orbital dynamics. In the context of orbit analysis of GPS-tracked Low Earth Orbiters geocentric Cartesian coordinates have to be transformed into instantaneous Keplerian elements. The paper presents a fast algorithm for the solution of this problem. For satellite motion considered in a relativistic framework the paper (SCHWARZE 1999) gives an excellent overview.

Numerical approximation methods

The numerical approximation aims at the development of efficient algorithms for the approximate solution of geodetic tasks. These tasks can be the approximate representation of a surface, of an integral operator or many other mathematical objects occurring in geodesy.

For geodetic computations on the surface of an ellipsoid of revolution or for the determination of the gravity field of the Earth from terrestrial gravity data the solution of certain integrals is a necessary intermediate step. In (RÖSCH, KERN 2000) three different techniques for the evaluation of elliptical integrals are compared. These methods are: series Expansion, numerical quadrature and Landen transformation. In terms of accuracy and numerical costs the Landen transforms outperforms the other two techniques. Similar investigations are made in (SCHMIDT H 2000). The paper (HECK 2002) gives a review over the different possibilities to represent the Earth's gravitational potential by various kinds of integral equations. The combination of all these integral equations approaches in a consistent and unified Meissl scheme is discussed in (KELLER 2002).

Advanced mathematical tools

Wavelet analysis as a tool for the analysis and interpretation of data and for the enhancement of numerical procedures has fully emerged in Geodesy only in the last few years. Several groups devote their work to the use of wavelet analysis for different purposes. The corresponding papers cover wavelet analysis both in the one-dimensional as well as in the two dimensional case, both for the Euclidean as

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well as for the spherical case. The purpose of the studies are a better interpretation of the corresponding data, the data compression or the improvement of the performance of well known numerical procedures.

Polar motion

One important area of wavelet applications is the improved analysis of polar motion.

The time series of the coordinates of the instantaneous position of the Earth's rotation axis is frequently analyzed by different kinds of wavelets. Such studies aim at the detection of time varying features of the polar motion.

Contributions, which belong to this group of investigations are (SCHMIDT, SCHUH 1999, 2000, 2001) and (SCHMIDT 2002). A special emphasis on the analysis of short-periodic variations in the Earth's polar motion is put on in the papers (SCHMITZ-HÜBSCH 2002) and (SCHMITZ-HÜBSCH, SCHUH 2002).

In a more general setting the time series of the polar motion can be considered as realizations of stochastic processes. A systematic extension of the theory of stochastic processes to wavelet bases can be found in (SCHMIDT 2000) and (SCHMIDT 2001a, b). The localization properties of wavelets enable the extension of the Wiener-Kolmogorov prediction to cases with a stationary signal but an in-stationary noise. These developments are reported in (KELLER 2000) and (KELLER 2001).

Wavelet analysis on the sphere

A vast amount of contributions about the wavelet analysis comes from the Geomathematical Group of the Kaiserslautern University. For years this group, led and inspired by W. FREEDEN, develops the theory and application of harmonic wavelets on the sphere. In the period from 1999 to 2003 the application of the now mature theory to the analysis of the Earth's gravitational and magnetical field was in the focus of the activities of this group.

Papers dealing with the spherical wavelet analysis of the Earth's magnetic field are (BAYER et al. 2001), (BAYER et al. 1999) and (BAYER 2000). General questions related to the representation of scalar and vectorial functions on a sphere by spherical wavelets are discussed in (BETH 2000), (FREEDEN et al. 1999a, b), (FREEDEN et al. 2001a), and (FREEDEN, MICHEL 1999).

Since practically, no data is noise free also the question of the de-noising of the given signal using spherical wavelets is discussed in the papers (FREEDEN et al. 2001b, c), (FREEDEN, MAIER 2002a, b), (FREEDEN, MICHEL 1999, 2000).

A great impact on geodetic research was made by the launches of the dedicated gravity field satellite missions CHAMP and GRACE. Naturally, these new data sources also are reflected in techniques for the analysis of these data.

Papers which are related to data collected from CHAMP or GRACE are (FREEDEN et al. 1999c), (FREEDEN, HESSE 2002), (FREEDEN et al. 2002a, b), (FREEDEN, MAIER 2002c),

(FREEDEN 1999, 2001), (MAIER 2002), (MAIER, MAYER 2002) and (MAYER, MAIER 2002).

Feature extraction and data compression

Many wavelet applications are based on the properties of wavelets to reflect local changes in the regularities of signals. Frequently, these local irregularities are related to features which have to be extracted from the signal. In the opposite way, in order to represent the main features of a signal it is sufficient to store those wavelet-coefficients, which are related to the main features and neglect all the others – leading to considerable data compression rates. In (MEIER 2003) wavelet compression for digital terrain models is studied. The degree of regularity of a signal can be read from its wavelet spectrum. This technique can be applied to the study of atmospheric turbulences, as it has been done in the papers (BETH et al. 1999) and (BETH et al. 2000).

Improvement of Numerical Techniques

Operators occurring in the formulation of geodetic problems are usually discretized with respect to some system of base functions. The discretized operator leads to a linear system of equations, which is usually large and fully occupied. If wavelets are used as base functions the resulting system will have a large number of very small entries and only few large entries. Neglecting the small entries leads to a sparse system, which can be used for pre-conditioning. This line has been followed in (KELLER 2002b). Due to the multi-resolution properties of wavelets, different components of the solution are associated to different scales of the base functions. In this way a natural connection between wavelet discretization and multi-grid iteration is established as it is reported in (KELLER 2002a). If even more for the representation of the given data and the unknowns solution different wavelet base systems are used, these systems can be chosen in such a way that the resulting matrix becomes diagonal. This is demonstrated in (GILBERT, KELLER 2000).

Geodetic boundary value problems

The world of geodetic measurements is much more complex than it used to be when geodetic boundary value problems (GBVPs) became the pivotal problems of geodesy. Consequently, the variety of GBVPs to be solved in geodesy has increased as well. A general overview was given by (LEHMANN 1999a) characterizing where we stand at the end of the 20th century.

This variety is reflected also by the contributions of German geodesists. We observe that in recent years Meissl-type diagrams or Meissl schemes became very popular. Several authors contributed to the completion and extension of such schemes organizing the spectral relationships of different geodetic observables at the geoid, at the surface of the Earth, and at satellite orbits (GRAFAREND 2001, KELLER 1999).

A beautiful overview of the solution of the Dirichlet, Neumann and Stokes problem for the Laplace equation on a sphere, cylinder and plane is due to RUMMEL and VAN GELDEREN (1999). The authors also discuss uniquely and

overdetermined GBVPs by least squares (VAN GELDEREN and RUMMEL 2000, 2001).

Overdetermined GBVPs arise when more functionals are measured than necessary and sufficient for a unique solution, an assumption more and more met in modern geodesy. In a spherical and constant-radius approximation, the analytical solution can be derived for a large class of geodetic observables.

Many contributions discuss how to make use of special geodetic observables like torsion balance measurements (LEHMANN 2000a, MENZ and KNOPSE 2002). Also two-boundary value problems prescribing observed data at the surface of the Earth and constant gravity potential (W_0) at the geoid, are continuously discussed (GRAFAREND et al. 1999).

LEHMANN (1999b) undertakes various studies on mixed GBVPs, in geodesy also known as altimetry-gravimetry boundary value problems. This takes care of the fact that the situation of data coverage is not the same all over the world, but is different e.g. on land and sea. The related problems are studied both analytically as well as numerically. One important problem, which has been posed in the geodetic literature before, is that in mixed GBVPs we do not know how to handle the vertical datum parameter. It was solved by LEHMANN (2000b), showing that with free vertical datum only two of the three classical altimetry-gravimetry problems are always uniquely solvable.

Besides these advanced and non-standard formulations, also classical geodetic BVPs deserve attention because we often have only the classical data available or the more complex world of geodetic measurements mentioned above is finally reduced to a sequence of theoretically well understood and numerically manageable classical cases. Contributions came from SEITZ (1999) investigating the standard approximation procedure adopted for the scalar free GBVP. A further contribution by ARDALAN and GRAFAREND (2001) treats the problem of ellipsoidal corrections for Bruns formula, which in its classical form is derived in spherical approximation only. LEHMANN (2001) proved that in its gravitational variant the scalar free GBVP exhibits much more features of ill-posedness than were known previously. Fortunately, when including the rotational part of the gravity potential the problem is mostly well-posed (apart from the well known three-dimensional nullspace).

A further focal point is the introduction of advanced numerical methods like boundary element method (BEM), so successfully applied in other engineering sciences. However, it is difficult to adapt the method to the special needs of geodesy. One important point is that the long wavelength part of the gravity field of the Earth is always determined from satellite data and not from boundary data. LEHMANN and KLEES (1999) addressed this problem by investigating various options, how to introduce a global reference field into BEM, but none of them seemed to suit all purposes. So the problem is left open. In the scalar free GBVP arises the ill-posedness (nullspace), which makes the BEM not immediately applicable. The problem was solved in (KLEES et al. 2001).

The mathematical theory of boundary value problems does not play the important role in geodesy which it used to play in the 2nd half of the previous century. This is because GBVPs are partly unable to reflect all aspects of the complex world of geodetic measurements. But still they deserve attention because they provide some deeper insight into some limiting cases of the situation we find in practical geodesy.

Inverse and improperly posed problems

Recently, German contributions to inverse and improperly posed problems in geodesy seem to focus on a small number of aspects only. The majority of these aspects is introduced by new geodetic satellite missions like CHAMP, GRACE or GOCE, providing gravity field related data of unprecedented resolution, accuracy and homogeneity.

One such aspect is certainly the use of multigrid methods for gravity field recovery. This allows the construction of fast solvers of the large and non-sparse systems of linear equations. The speed of convergence of iterative solvers becomes independent of the discretization level. First steps are made by KUSCHE and RUDOLPH (2000a, b).

A PhD thesis (RUDOLPH 2000) is devoted to multigrid methods for gravity field recovery in a regional and global scale. For this purpose a hierarchical parametrization with space-localizing base functions on an equi-angular spherical grid are introduced and the corresponding multigrid algorithm is formulated. Computations with simulated data sets prove that the implementation is workable and successful.

Moreover, the multigrid methods yield as a by-product a well-defined sequence of coarser approximations of the gravity field. This is further investigated in (KUSCHE 2001, 2002), where it is shown that for two regional gravity inversions from simulated data the multigrid solvers run much faster than conjugate gradient solvers with conventional preconditioners.

A further aspect is regularization of the problem of gravity field recovery from satellite data, which is naturally unstable and leads to ill-conditioned normal equations. Regularization is already touched in several of the papers mentioned above, but is more intensely studied in (KUSCHE and KLEES 2002a, b). The method of Tikhonov regularization is applied, and the regularization parameter is chosen both according to the L-curve criterion as well as by generalized cross validation (GCV). It is found that randomized GCV performs optimally while the numerical cost is limited. All these results are derived by numerical experiments with GOCE data.

KUSCHE and MAYER-GÜRR (2002) modify the procedure by introducing Lanczos method for the iterative solution of the problem. The algorithm is in fact LSQR, where Lanczos method is only used to bi-diagonalize matrices. It is demonstrated by numerical experiments on a regional gravity recovery from simulated GOCE data that it performs well in combination with Tikhonov regularization and randomized GCV.

KOCH and KUSCHE (2002) address the problem of regularization in the framework of Bayesian inference on variance components. In this way we obtain also weighting factors

for different data types in a natural manner, and not only the estimates themselves but also confidence intervals. Test computations with GOCE and GRACE demonstrate the validity of this approach. KOCH (2002) introduces the interesting method of applying a Monte Carlo simulation for the determination of the confidence interval of the regularization parameter found by GCV. This is recommendable because the CGV is iterative by nature and does not allow the explicit computation of posterior density functions for the regularization parameter.

A final aspect is analyzed in (ILK et al. 2000, KUSCHE et al. 2000): the combination of data from different origins like space-borne and terrestrial data in the presence of ill-posedness. Some open questions exist when detecting the contributions of the different data sets and merging to the final solution. The papers try to clarify these questions again based on empirical investigations by numerical tests.

The subject is treated at length in a habilitation thesis (KUSCHE 2002).

One contribution by (LEHMANN 1999c) is a little bit outstanding when compared to the contributions above: The maximum entropy method is applied to the inverse problem of density determination for the Earth and terrestrial planets from various sources of data (geodetic, geophysical). As a sample problem, an ellipsoidal density model for the Mars is generated from the best available data.

References

- ARDALAN A.A., GRAFAREND E.W.; *Ellipsoidal geoid undulations (ellipsoidal Bruns formula)*. Journal of Geodesy, Vol. 75(2001), No. 9-10, pp. 544-552
- AUSTEN G., GRAFAREND E.W.; *Fast Inverse Kepler Transformation*, Artificial Satellites 36(2001), 99-114
- BAYER M., FREEDEN W., MAIER T.; *A Vector Wavelet Approach in Iono- and Magnetospheric Geomagnetic Satellite Data*. Journal of Atmospheric and Solar-Terrestrial Physics, (63), 581-597, 2001.
- BAYER M., FREEDEN W., MAIER T.; *Wavelet analysis of the geomagnetic field within source regions of ionospheric and magnetospheric currents*. Berichte d. Arbeitsgruppe Technomathematik, Fachbereich Mathematik, Univ. Kaiserslautern, Bericht No. 217, (1999)
- BAYER M.; *Geomagnetic Field Modelling From Satellite Data by First and Second Generation Wavelets*. PhD thesis, University of Kaiserslautern, Geomathematics Group, 2000. haker Verlag, Aachen.
- BETH S.; *Multiscale Approximation by Vector Radial Basis Functions on the Sphere*. PhD thesis, University of Kaiserslautern, Geomathematics Group, 2000. haker Verlag, Aachen.
- BETH S., BOOS T., FREEDEN W., CASOTT N., DEUSSEN D., WITTE B.; *On the wavelet determination of scale exponents in energy spectra and structure functions and their application to CCD camera data*. In: Schwarz K.P. (ed.), Geodesy Beyond 2000 – The Challenges of the First Decade. International Association of Geodesy Symposia, Vol. 121, Springer-Verlag, Berlin Heidelberg, pp 221-226.
- BETH S., CASOTT N., DEUSSEN D., FREEDEN W., WITTE B.; *Digital Meteorological Sensors for the Detection of Atmospheric Turbulence and Their Geodetic Application*. In: Altan-Gründig, editor, 3rd German-Turkish Joint Geodetic Days, 1:91-99, 1999.
- FREEDEN W.; *Multiscale Modelling of Spaceborne Geodata*. Teubner, Stuttgart, Leipzig, 1999.
- FREEDEN W.; *Multiscale Modelling of GOCE-DATA-Products*, In: ESA-Proceedings of the International GOCE User Workshop, ESTEC, Noordwijk, ESA WPP-188, 111-126, 2001.
- FREEDEN W., GLOCKNER O., LITZENBERGER R.; *A General Hilbert Space Approach to Wavelets and its Application in Geopotential Determination*. Numer. Funct. Anal. Optimiz., (20): 853-879, 1999.
- FREEDEN W., GLOCKNER O., LITZENBERGER R.; *Multiscale Modelling From Geopotential Data*. In: Mathematical Research, Vol. 107. Advances in Multivariate Approximation, W. Häußmann, K. Jetter, M. Reimer, editors, Wiley-VCH, 151-174, (1999).
- FREEDEN W., GLOCKNER O., THALHAMMER M.; *Multiscale Gravitational Field Recovery from GPS-Satellite-to-Satellite Tracking*. Studia Geophysica et Geodaetica, (43): 229-264, 1999
- FREEDEN W., GROTEN E., MICHEL V., KABOODVAND A.; *Geoidal Reconstruction, Decomposition, Fast Computation, and Noise Cancellation by Harmonic Wavelets*. Studia Geophysica et Geodaetica (accepted), 2001
- FREEDEN W., HESSE K.; *On the Multiscale Solution of Satellite Problems by Use of Locally Supported Kernel Functions Corresponding to Equidistributed Data on Spherical Orbits*. Studia Scientiarum Mathematicarum Hungarica (39), 37-74, 2002.
- FREEDEN W., MAIER T.; *Spectral and Multiscale Signal-to-Noise Thresholding of Spherical Vector Fields*. Computational Geosciences, (accepted), 2002
- FREEDEN W., MAIER T.; *On Multiscale Denoising of Spherical Functions: Basic Theory and Numerical Aspects*. Electronic Transactions on Numerical Analysis (ETNA) 14:40-62, 2002.
- FREEDEN W., MAIER T., MAYER C.; *Multiscale Crustal Field Determination from CHAMP Vector Magnetic Data*. Geophysical Research Letters. submitted), 2002.
- FREEDEN W., MAIER T.; *SST-Regularisierung durch Multi-resolutionstechniken auf der Basis von CHAMP-Daten*. Berichte der AGTM 252 (Weiterbildung), 2002
- FREEDEN W., MAIER T., ZIMMERMANN S.; *A Survey on Wavelet Methods for (Geo)Applications*. Revista Mathematica Complutense. (accepted), 2001.
- FREEDEN W., MICHEL V.; *Constructive approximation and numerical methods in geodetic research today – an attempt at a categorization based on an uncertainty principle*. Berichte d. Arbeitsgruppe Technomathematik, Fachbereich Mathematik, Univ. Kaiserslautern, Bericht No. 208; also in Journal of Geodesy, Vol. 73 (1999), No. 9, pp. 452-465.
- FREEDEN W., MICHEL V.; *Least squares geopotential approximation by windowed Fourier transform and wavelet transform*. Berichte d. Arbeitsgruppe Technomathematik, Fachbereich Mathematik, Univ. Kaiserslautern, Bericht No. 216, (1999)
- FREEDEN W., MICHEL V.; *Least-squares Geopotential Approximation by Windowed Fourier Transform and Wavelet Transform*. In: Springer Lecture Notes in Earth Sciences, R. Klees and R. Haagmans, editors, (90): 189-241, 2000.

- FREEDEN W., MICHEL V., NUTZ H.; *Satellite-to-Satellite Tracking and Satellite Gravity Gradiometry (Advanced Techniques for High-Resolution Geopotential Field Determination)*. Journal of Engineering Mathematics (43), 19-56, 2002
- FREEDEN W., MICHEL V., STENGER M.; *Multiscale Signal-to-Noise Thresholding*. Acta Geodaetica et Geophysica Hungarica (36): 55-86, 2001.
- GILBERT A., KELLER W.; *Deconvolution with wavelets and vaguelettes*. Journal of Geodesy 74 (2000) 3/4, 306-320
- GRAFAREND E.W.; *Gaußsche flächennormale Koordinaten im Geometrie- und Schwereräum*, ZfV 125(2000), 2, 136-139
- Grafarend E.W.; Gauss surface normal coordinates in geometry and gravity space. ZfV 126(2001), 6, 373-382
- GRAFAREND E. W.; *The spherical horizontal and spherical vertical boundary value problem – vertical deflections and geoidal undulations – the completed Meissl diagram*. Journal of Geodesy 75 (2001) 7-8, 363-390
- GRAFAREND E. W., ARDALAN A., SIDERIS M. G.; *The spheroidal fixed-free two-boundary-value problem for geoid determination (the spheroidal Bruns' transform)*. Journal of Geodesy 73 (1999) 10, 513-533
- GRAFAREND E. W., HENDRICKS A., GILBERT A.; *Transformation of conformal coordinates of type Gauß-Krüger or UTM from local datum (regional, National, European) to global datum (WGS84, ITRF 96)*, AVN 6(2000), 218-222
- Grafarend E.W.; Sensitive control of high-speed-railway track. Part I: Local representation of the clothoid., AVN 2(2002), 61-70
- GRAFAREND E.W.; Sensitive control of high-speed-railway track. Part II: Minimal distance mapping of a point close to the clothoid., AVN 3(2002), 85-91
- HECK B.; *Integral Equation Methods in Physical Geodesy*. In: Grafarend E.W., Krumm F.W., Schwarze V.S.(Eds.); Geodesy – The Challenge of the 3rd Millennium, Springer Verlag Berlin 2002
- ILK K.H., KUSCHE J., RUDOLPH S.; *A contribution to data combination in ill-posed downward continuation problems*. IUGG 99 Joint Symposium JSA-37 (Earth's Gravity and Magnetic Field from Space), Journal of Geodynamics 33 (2002) 1-2, 65-74.
- KELLER W.; *Geodetic Pseudodifferential Operators and the Meissl Scheme*, In: Grafarend E.W., Krumm F.W., Schwarze V.S.(Eds.); Geodesy- The Challenge of the 3rd Millennium, Springer Verlag Berlin 2002
- KELLER W.; *A wavelet approach to non-stationary collocation*. In: Schwarz K.P. (ed.), Geodesy Beyond 2000 – The Challenges of the First Decade. International Association of Geodesy Symposia, Vol. 121, Springer-Verlag, Berlin Heidelberg (2000), 208-213.
- KELLER W.; *A Wavelet Solution to 1D Non-stationary Collocation With an Extension to the 2D case*. In: Sideris M.. (ed.), Gravity, Geoid and Geodynamics 2000. International Association of Geodesy Symposia, Vol. 123, Springer-Verlag, Berlin Heidelberg (2001), pp. 79 -85.
- KELLER W.; *A Wavelet Approach for the Construction of Multi-Grid Solvers for Large Linear Systems*. In: J. Adam, K.-P. Schwarz (Eds.): Vistas for Geodesy in the New Millennium. AG Symposia Vol. 125. pp 265-270. Springer Verlag Berlin Heidelberg 2002.
- KELLER W.; *The Use of Wavelets for the Acceleration of Iteration Schemes*. Hotine-Marussi-Symposium, Matera 2002, (accepted)
- KLEES R., VAN GELDEREN M., LAGE C., SCHWAB C.; *Fast numerical solution of the linearized Molodensky problem*. Journal of Geodesy 75 (2001) 7-8, 349-362
- RÖSCH N., KERN M.; *Die direkte Berechnung elliptischer Integrale*. ZfV 125(200), 209 – 213
- KOCH K.-R.; *Monte-Carlo-Simulation für Regularisierungsparameter*. Zeitschrift für Vermessungswesen, Vol.127, No.5, 2002, pp 305-309
- KOCH K.-R., KUSCHE J.; *Regularization of geopotential determination from satellite data by variance components*. Journal of Geodesy 76 (2002) 5, 259-268
- KUSCHE J.; *On fast multigrid iteration techniques for the solution of normal equations in satellite gravity recovery*. IUGG 99 Joint Symposium JSA-37 (Earth's Gravity and Magnetic Field from Space), Journal of Geodynamics 33 (2002) 1-2, 173-186
- KUSCHE J.; *Implementation of multigrid solvers for satellite gravity anomaly recovery*. Journal of Geodesy 74 (2001) 11/12, 773-782
- KUSCHE J.; *Inverse Probleme bei der Gravitationsfeldbestimmung mittels SST- und SGG-Satellitenmissionen Habilitationsschrift, DGK C, Nr. 548, 2002*
- KUSCHE J., ILK K.H., RUDOLPH S.; *Impact of terrestrial data on future satellite gravity field solutions*. In: Rummel R., Drewes H., Bosch W., Hornik, H. (eds.): Towards an Integrated Global Geodetic Observing System IGGOS). IAG symposia, Vol. 120, Springer, Berlin, pp. 189-192.
- KUSCHE J., KLEES R.; *Regularization of gravity field estimation from satellite gravity gradients*. Journal of Geodesy 76 (2002a) 6-7, 359-368
- KUSCHE J., KLEES R.; *On the Regularization Problem in Gravity Field Determination from Satellite Gradiometric Data*. In: J. Adam, K.-P. Schwarz (Eds.): Vistas for Geodesy in the New Millennium. AG Symposia Vol. 125. pp 175-180. Springer Verlag Berlin Heidelberg 2002b.
- KUSCHE J., MAYER-GÜRR, T.; *On the Iterative Solution of Ill-Conditioned Normal Equations by Use of Lanczos Methods*. In: J. Adam, K.-P. Schwarz (Eds.): Vistas for Geodesy in the New Millennium. AG Symposia Vol. 125. pp 248-252. Springer Verlag Berlin Heidelberg 2002.
- KUSCHE J., RUDOLPH S.; *The multigrid method for satellite gravity field recovery*. In: Schwarz K.P. (ed.), Geodesy Beyond 2000 – The Challenges of the First Decade. International Association of Geodesy Symposia, Vol. 21, Springer-Verlag, Berlin Heidelberg, pp. 186-190.
- KUSCHE J., RUDOLPH S.; *Satellite gravity anomaly recovery using multigrid methods*. In: M.G. Sideris (ed.): Gravity, Geoid and Geodynamics 2000, GGG2000 IAG International Symposium, Banff, Alberta, Canada, July 31 – August 4, 2000. International Association of Geodesy Symposia, Vol. 123, Springer, Berlin-Heidelberg-New York etc., 2001, pp. 91-96.
- LEHMANN R.; *Boundary-value problems in the complex world of geodetic measurements*. Journal of Geodesy 73 (1999a) 9, 491-500
- LEHMANN R.; *Studies on the altimetry-gravimetry problems for geoid determination*. Physics and Chemistry of the Earth, Part A: Solid Earth and Geodesy, 24(1999), 47-52.
- LEHMANN R. (1999c): *Maximum entropy density determination for the Earth and terrestrial planets*. Studia geoph. et geod. 43, No. 1, pp. 35-60.

- LEHMANN R., KLEES R.; *Numerical solution of geodetic boundary value problems using a global reference field*. Journal of Geodesy 73 (1999) 10, 543-554
- LEHMANN R.; *On the allocation and assessment of absolute values for geoid determination using torsion balance measurements*. In: J. Menz (Ed.): *Angewandte Geostatistik in Bergbau, Geologie, Geophysik, Geodäsie und Umweltschutz*(2000).
- LEHMANN R.; *Altimetry-gravimetry problems with free vertical datum*. Journal of Geodesy 74 (2000) 3/4, 327-334
- LEHMANN R.; *A new type of non-uniqueness for the scalar geodetic boundary value problem*. Journal of Geodesy 75 (2001) 9/10, 527-532
- MAIER T.; *Multiscale Geomagnetic Field Modelling From Satellite Data: Theoretical Aspects and Numerical Applications* (Universität Kaiserslautern dem FB Mathematik eingereichte Dissertation), 2002
- MAIER T., MAYER C.; *Multiscale Downward Continuation of CHAMP FGM-Data for Crustal Field Modelling*. Proceedings of the 1st CHAMP Science Meeting (accepted), 2002, Mathematische Geologie Band 5, C-Press Verlag Dresden
- MAYER C. MAIER T.; *Multiscale Determination of Radial Current Distribution from CHAMP FGM-Data*. Proceedings of the 1st CHAMP Science Meeting (accepted), 2002
- MEIER S.; *Zur K-Frage: Kompressionsraten der schnellen Wellenformtransformation aus statistischer Sicht*. ZfV, 128(2003), No.2, 31-39
- MENZ J., KNOSPE S.; *Lokale Bestimmung des Geoids aus terrestrischen Gradiometermessungen unter Nutzung geostatistischer Methoden*. ZfV, Vol.127, No.5, 2002, pp 321-332
- RUDOLPH S.; *Regionale und globale Gravitationsfeldanalyse hochauflösender Satellitendaten mittels Mehrgitterverfahren*. Deutsche Geodätische Kommission, Reihe C, Nr. 527 (2000), München.
- RUMMEL R., VAN GELDEREN M.; *From the generalized Bruns transformation to variations of the solution of the geodetic boundary value problem*. in: Krumm, F., Schwarze, V.S. (eds.): *Quo vadis geodesia ...?*, Festschrift for E.W. Grafarend on the occasion of his 60th birthday. Technical Reports of the Dept. of Geodesy and Geoinformatics, Univ. of Stuttgart, 1999, Part 2, pp. 397-412.
- SCHMIDT H.; *Berechnung geodätischer Linien auf dem Rotationsellipsoid im Grenzbereich diametraler Endpunkte*. ZfV, 125(2000), 2, 61-64
- SCHMIDT M., SCHUH H.; *Wavelet-Analyse der mit VLBI beobachteten Nutationsreihen*, ZfV 124(1999), 1, 24-30
- SCHMIDT M., SCHUH H.; *Abilities of Wavelet Analysis for Investigating Short-period Variations of Earth Rotation*, IERS (2000) Technical Note No 28, 73-80
- SCHMIDT M., SCHUH H.; *Wavelet-Analyse von Erdrotationschwankungen*, ZfV 126(2001), 1, 94-100
- SCHMIDT M.; *Wavelet Analysis of Stochastic Signals*, IERS (2000) Technical Note No 28, 65-71
- SCHMIDT M.; *Ein Beitrag zur zweidimensionalen Wavelet-Analyse von Zufallsprozessen*, ZfV 126(2001), 270-275
- SCHMIDT M.; *Grundprinzipien der Wavelet-Analyse und Anwendungen in der Geodäsie*, Shaker-Verlag, Reihe Geodäsie Band 9, 2001
- SCHMIDT M.; *Wavelet-Analyse von Zeitreihen*, In: Schuh, H., Soffel, M. and Hornik, H. (eds.); *Vorträge im 4. DFG-Rundgespräch im Rahmen des Forschungsvorhabens 'Rotation der Erde' zum Thema 'Wechselwirkungen im System Erde'*. German Geodetic Commission (DGK), Series A, No 118, 46-56, 2002
- SCHMITZ-HÜBSCH H.; *Wavelet-Analysen der Erdrotationsparameter im hochfrequenten Bereich*. Schriftenreihe der Deutschen Geodätischen Kommission, Reihe, Heft A 118, München 2002.
- SCHMITZ-HÜBSCH H., SCHUH H.; *Seasonal and short-period fluctuations of Earth Rotation investigated by Wavelet Analysis*. In: Grafarend E.W., Krumm F.W., Schwarze V.S.(Eds.); *Geodesy- The Challenge of the 3rd Millenium*, Springer Verlag Berlin 2002
- SCHWARZE V. S.; *Satellite geodesy on curved space-time manifolds*. Earth-fixed charts. Journal of Geodesy 73 (1999) 11, 594-602
- SEITZ K.; *Ellipsoidal and topographical effects in the scalar free geodetic boundary value problem*. In: Krumm, F., Schwarze, V.S. (eds.): *Quo vadis geodesia ...?*, Festschrift for E.W. Grafarend on the occasion of his 60th birthday. Technical Reports of the Dept. of Geodesy and Geoinformatics, Univ. of Stuttgart, 1999, Part 2, pp. 439-452.
- VAN GELDEREN M., RUMMEL R.; *A general least-squares solution of the geodetic boundary value problems*. In: Schwarz K.P. (ed.), *Geodesy Beyond 2000 – The Challenges of the First Decade*. International Association of Geodesy Symposia, Vol. 121, Springer-Verlag, Berlin Heidelberg, 2000, pp. 171-178.
- VAN GELDEREN M., RUMMEL R.; *The solution of the general geodetic boundary value problem by least squares*. Journal of Geodesy 75 (2001) 1, 1-11

Stochastic methods of data evaluation

S. MEIER¹

Introduction

In this part of the report, works on the evaluation and processing of geodetic data, more generally, geo-data, and on the assessment of their safety, reliability and accuracy – in a word, their quality – are listed. Processing of mass data, which are obtained through current terrestrial, and more and more, outer-terrestrial measuring and sampling methods, requires advanced procedures well adapted to the actual data structure of adjustment (over-determined problems) and prediction (under-determined problems). The first-mentioned procedures are based on statistical estimation theory: parameter and interval estimation as well as hypothesis testing (preferably, but not exclusively by linear models). Here, Bayesian statistics with its known advantages over conventional statistics is gaining ground. Therefore, works on Bayes' statistics in geodesy and image processing are worthy of particular note. The second-mentioned procedures rest on stochastic process and signal theory. If the sampled data are relevant for geosciences, these procedures can also be summed up as geostatistics. Works focus, in a way, on the integral transformations, more recently the wavelet transformation – a considerable progress in analysing and processing of signals with complex structures.

Not quite half of the works deal with the fundamentals. These works are listed in the first two sections, separated into two subject fields, despite of many links or equivalencies as to prior information of second order such as covariance functions and matrices, regions of significance or test strategies. Three further sections list applications in all geodetic sciences from satellite geodesy to digital cartography. Only papers were included that substantially contribute to the adaption of the procedures to problems of current interest or to methodology, surpassing pure routine works. Finally, the textbooks published in the period under review are presented.

Parameter estimation and statistical inference

It is well known that different adjustment models can be transformed into each other. KAMPMANN and RENNEN (1999) say something about this 'old, new' topic. Also, the adjustment principle is equivalent, as C. F. GAUSS had already brought out, to certain principles of mechanics. KAMPMANN and KRAUSE (2000) analyse the equivalency of the so-called balanced adjustment and the law of universal gravitation. It is interesting that equivalencies to the extremal principles of physics exist even in digital cartography (see below).

Geodetic observations frequently have to meet geometrical restrictions, the classification and consideration of which in adjustment problems is dealt with by JURISCH et al. (1999, 2000), especially for multiple observations by KAMPMANN and RENNEN (2000). Geometry analyses can also contribute to outlier testing or redundancy testing (JURISCH and KAMPMANN 2001, 2002). The parameters to be estimated can more or less sensibly react to the stochastic model chosen (KUTTERER 1999, KUTTERER and SCHÖN 1999) or the auto-correlations introduced (KUHLMANN 2001). In addition to conventional statistics, Bayesian statistics is becoming more and more important. In a survey, KOCH (1999b) illustrates the basic principles and in another report (KOCH 2000c), some numerical procedures of Bayesian statistics.

While the parameter estimation, stochastic inference and quality assessment (MEIER 1999) are dominantly performed in linear models (collection of examples by KOCH 2000b), non-linear procedures are also have the right to exist. HETTNER and BENNING (2001) succeeded in expanding the convergence region of the non-linear adjustment procedures. LENK (2001) deals with the fast multiplication of big matrices in adjustment calculations and SCHMIDT (1999) presents an approximative solution of normal equations by eigenvalue decomposition.

Stochastic signal analysis and geostatistics

The analysis of stochastic signals, or realizations of stochastic processes, respectively, has also been known (in the narrower sense) as analysing of time series. CASPARY (2000) surveys the analysis of geodetic time series. Their variation and correlation qualities are described by functions of moments of second order. BIAN and MENZ (1999), MENZ and KOLESNIKOW (2002) deal with the estimation of covariance functions, SCHWIEGER (2001), GRAFAREND and MARINKOVIC (2002) with the construction of synthetic covariance matrices, FÖRSTNER and MOONEN (1999) with their metric. The analysis of two-dimensional processes is also important for digital image processing (see below) and in geophysics, geology and mining industries as well. In these fields it is presented as geo-modelling (MENZ 1999) or geostatistics (MENZ 2000, MENZ and KNOSPE 2002). Tools originating from stochastic geometry are also used, such as Voronoi diagrams for classification and interpolation (ROSCHLAUB 1999).

In recent years, the wavelet transformation has been used as a locally analysing and approximating as well as data compressing integral transformation to process signals of complex structure (SCHMIDT 2000, 2001c), above all to

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analyse Earth's rotation variations (SCHMIDT and SCHUH 2000, SCHMIDT 2001a). Not only the signals themselves, but also their moments of second (or higher, if applying) order can be transformed into the wavelet domain via convolution. Therefore statistical analysing along with hypothesis testing is also possible in the wavelet domain (SCHMIDT 2001b, 2002). The data compression of the wavelet transformation is based on thresholding. For that reason also compression rates can be estimated in advance using statistical aids (MEIER 2003).

Geodesy and surveying

In operational geodesy space methods are dominant, especially for the solution of global and regional problems. Attention focuses on the Global Positioning System (GPS) including efforts towards increasing the system's accuracy and reliability: ANGERMANN and BECKER (2000) investigate the accuracy and systematic effects in extended GPS networks, SCHWIEGER (1999) presents an error model of repeated GPS observations considering correlations, AWANGE (2002) treats the adjustment of non-linear GPS/LPS observations. Resolution of ambiguities is of paramount significance. New methods for the validation of ambiguities in the acceptance and discrimination tests were developed using methods of conventional and Bayesian statistics as well (GUNDLICH 2002, GUNDLICH and KOCH 2002). Current and future satellite missions require preliminary investigations on the error budget, e.g. concerning gradiometry (HESS and KELLER 1999), further methodical investigations, e.g., into the geodetic boundary value problem (VAN GELDEREN and RUMMEL 2001), spectral methods (CHUI and LELGEMANN 2003), and regularization techniques, e.g. by means of variance components (KOCH and KUSCHE 2002).

Coordinate systems, coordinate transformations, datum transformations of geodetic networks are part of the standard repertoire of geodesy: KOCH (2002) works on the three-dimensional Helmert transformation of variable coordinates in both the Gauss-Helmert- and Gauss-Markov models, presumably in reaction to previous works by LENZMANN (2001), LENZMANN and LENZMANN (2001), the latter including critical comments by J. REINKING and by K.-R. KOCH. Other papers on the optimal three-dimensional transformation were written by FRÖHLICH and SPATA (2002), and AWANGE and GRAFAREND (2002).

Even in local surveying GPS dominates the conventional methods generally well-investigated, while exceptions prove the rule. So SCHLICHTING (1999) analyses the accuracy and optimization of intersection in deformation measurements, STEGELMANN (2000) the reliability of surveying for cadastral purposes. HEISTER (2002) concerns oneself with precision standards of geodetic instruments, NITSCHKE (2002) with robotics, and HEISTER and STAIGER (2001) present quality management strategies.

Digital photogrammetry and image processing

Processing of all kinds of images also requires adjustment techniques and error estimation to be used: ZEITLER (1999) describes the simultaneous adjustment of the global three-

dimensional network of the planet Mars, MÜLLER and BENNING (1999) work on the homogenization of three-dimensional scenarios by the method of least squares. To estimate model parameters in digital image analysis, HELLWICH (1999) uses the simulated annealing – a method with a physical analogy, namely the step-by-step change of a system's energy level. Accuracy investigations into the GPS/INS integration in airborne photogrammetry were carried out by CRAMER (2001), into correlation procedures in digital image processing by CASOTT and PRENTING (1999). Compression of digital image data to be stored is usual: KIEFNER (2001) analyses the influence of different compression procedures upon the quality of digital point transition.

In recent years, modelling and acquisition of semantic information from images were speeded up, e.g. by means of stochastic models and statistical analysing procedures: recognition and reconstruction of buildings using Bayesian networks by KULSCHWESKI (1999), using combined Markovian random fields by BRUNN (2001). In order to segment and interpolate digital images, KLONOWSKI (1999) also uses Markovian random fields.

Digital topography and cartography

The terrestrial topographic sampling methods have been replaced almost completely by space methods culminating in The Shuttle Radar Topography Mission. Several authors work on the validation and quality assessment of the digital terrain models derived from the SRTM data: KLEUSBERG and KLAEDTKE (1999a, b), REICH (2001), KOCH and HEIPKE (2001), KOCH et al. (2002). Apart from the radar techniques, laser scanning has been further developed concerning spacing and accuracy: MAAS (2001) assesses the quality of the airborne laser scanning using matching techniques by least squares, MEIER (2000) the quality of snakes-approximated terrain profiles with point breaks. While, on the one hand, different methods can be used for a reliable decomposition of signals (STUBENVOLL 2000), the possibility is seen to emerge that, on the other hand, the approximation of the relief can be improved by the combination of space methods with different sampling and error characteristics (WENDT 2002).

For cartographic purposes, adjustment procedures were used directed at two kinds of objectives: for the homogenization of digitized data from maps of different sources and precision (HETTWER and BENNING 2000, KAMPSHOFF and BENNING 2002) and for the computer-aided generalization (SEESTER 2000), particularly to displace point, line and area objects in scale-dependent presentations (SEESTER 2001a, b). In addition to L_1 -norm and L_2 -norm solutions, also solutions exist based on the universal energy minimum principle (BURGHARDT 2001). Precision and reliability of historical maps were analysed by BEINEKE (2001) and PENZKOFER et al. (2001).

Textbooks

The well-known textbook by K.-R. KOCH on Parameter Estimation and Hypothesis Testing in Linear Models was published in the 2nd updated and enlarged English edition

(KOCH 1999a; 3rd German edition 1997 already). Among others, a section on robust estimates contributes to actualization. The same author published an introduction into Bayesian statistics in German (KOCH 2000a, after the English book on Bayesian Inference with Geodetic Applications of 1990).

The adjustment book by NIEMEIER (2002) is directed, as a basic course, at students and engineers of surveying and geoinformatics. In addition to common fundamentals also advanced methods, such as robust estimates, datum transformations, Kalman filters, are presented in a didactically attractive manner. Then, the course in surveying by WITTE and SCHMIDT (2000) was published in the 4th edition. This course presents not only surveying, but also basic methods of statistics in civil engineering. The book by BENNING (2002) is directed at the same people: It teaches statistics in geodesy, geoinformatics and civil engineering.

Beside the pure textbooks we advise to an extended report on data analysis methods in geodesy by DERMANIS and RUMMEL (2000).

References

- ANGERMANN D., BECKER M. (2000): *Untersuchungen zu Genauigkeit und systematischen Effekten in großräumigen GPS-Netzen am Beispiel von GEODYSSSEA*. Zeitschrift für Vermessungswesen, 125, 3, 88-95.
- AWANGE J.L., GRAFAREND E.W. (2002): *Linearized Least Squares and nonlinear Gauss-Jacobi combinatorial algorithm applied to the 7-parameter datum transformation $C_7(3)$ problem*. Zeitschrift für Vermessungswesen 127, 2, 109-116.
- AWANGE J.L. (2002): *Gröbner bases, Multipolynomial resultants and the Gauss-Jacobi combinatorial algorithms – adjustment of nonlinear GPS/LPS observations*. Schriftenreihe der Institute des Studiengangs Geodäsie und Geoinformatik der Universität Stuttgart, Report Nr. 2002.1
- BEINEKE D. (2001): *Verfahren zur Genauigkeitsanalyse für Altkarten*. Schriftenreihe Studiengang Geodäsie und Geoinformation, Universität der Bundeswehr München, Heft 71, Neubiberg.
- BENNING W. (2002): *Statistik in Geodäsie, Geoinformation und Bauwesen*. 309 S., Herbert Wichmann Verlag, Heidelberg.
- BIAN S., MENZ J. (1999): *Determining the parameter of a covariance function by analytical rules*. Zeitschrift für Vermessungswesen, 124, 7, 211-216.
- BRUNN A. (2001): *Semantik-basierte Gebäudeerfassung mit verkoppelten Markoff-Zufallsfeldern*. Dissertation, Universität Bonn. BURGHARD D. (2001): *Automatisierung der kartographischen Verdrängung mittels Energieminimierung*. Deutsche Geodätische Kommission, Reihe C, Heft Nr. 536, München.
- CASOTT N., PRENTING J. (1999): *Genauigkeitssteigerung beim Korrelationsverfahren in der digitalen Bildverarbeitung*. Photogrammetrie, Fernerkundung, Geoinformation, 2, 101-112. CASPARY W. (2000): *Zur Analyse geodätischer Zeitreihen*. Schriftenreihe des Studiengangs Geodäsie und Geoinformatik der Universität der Bundeswehr, Heft 60-1, 1-26.
- CRAMER M. (2001): *Genauigkeitsuntersuchungen zur GPS/INS-Integration in der Aerophotogrammetrie*. Deutsche Geodätische Kommission, Reihe C, Heft Nr. 537, München.
- CUICH., LELGEMANN D. (2003): *Die Reduktion von GRACE-SST Daten zwecks Aufbereitung zu einer Spektralanalyse*. Zeitschrift für Vermessungswesen, 128, 1, 40-46.
- DERMANIS A., RUMMEL R. (2000): *Data Analysis Methods in Geodesy*. In: Geomatic Models for the Analysis of Data in the Earth Sciences (eds: A. DERMANIS, A. GRÜN, F. SANSÒ), Lecture Notes in Earth Sciences, 95, 17-92, Springer Verlag, Heidelberg.
- FÖRSTNER W., MOONEN B. (1999): *A Metric for Covariance Matrices*. Schriftenreihe der Institute des Studiengangs Geodäsie und Geoinformatik der Universität Stuttgart, Report Nr. 1999. 6-1, 113-128.
- FRÖHLICH H., SPATA M. (1999): *Optimale Bestimmung von geodätischen Datum-Shift-Parametern mittels L2- und L4-Norm*. Allgemeine Vermessungsnachrichten, 106, 11-12, 390-393. GELDEREN M. VAN, RUMMEL R. (2001): *The Solution of the general geodetic boundary value problem by least squares*. Journal of Geodesy, 75, 1-11 (Corrections in Journal of Geodesy, 2002, 76, 121-122).
- GRAFAREND E.W., MARINKOVIC P.S. (2002): *The three-dimensional Taylor-Karman criterion matrix (potential type, 1st order Markov process): Analysis of LEO satellite ephemerides and of space gravity spectroscopy*. In: Festschrift zum 65. Geburtstag von Prof. Dr.-Ing. habil. Siegfried Meier, Institut für Planetare Geodäsie, TU Dresden, 39-46.
- GUNDLICH B. (2002): *Statistische Untersuchung ganzzahliger und reellwertiger unbekannter Parameter im GPS-Modell*. Deutsche Geodätische Kommission, Reihe C, Heft Nr. 549, München.
- GUNDLICH B., KOCH K.-R. (2002): *Confidence regions for GPS baselines by Bayesian Statistics*. Journal of Geodesy, 76, 55-62.
- HEISTER H., STAIGER R. (eds.; 2001): *Qualitätsmanagement in der geodätischen Messtechnik*. DVW Schriftenreihe, 42, Konrad Wittwer Verlag, Stuttgart.
- HEISTER H. (2002): *Zu Genauigkeitsangaben bei geodätischen Instrumenten*. Mitteilungen aus den Geodätischen Instituten der Universität Bonn, Nr. 89, 73-81.
- HELLWICH O. (1999): *Model parameter estimation for Digital Image Analysis Using Simulated Annealing*. Photogrammetrie, Fernerkundung, Geoinformation, 6, 371-379.
- HESS D., KELLER W. (1999) *Gradiometrie mit GRACE, Teil I, Fehleranalyse künstlicher Gradiometerdaten*. Zeitschrift für Vermessungswesen, 124, 5, 137-144.
- HETTWER J., BENNING W. (2000): *Nachbarschaftstreue Koordinatenberechnung in der Kartenhomogenisierung*. Allgemeine Vermessungsnachrichten, 107, 194-197.
- HETTWER J., BENNING W. (2001): *Erweiterung des Konvergenzbereichs bei nichtlinearen Gleichungsaufgaben*. - Allgemeine Vermessungsnachrichten, 7, 254-258.
- JURISCH R., KAMPMANN G., LINKE J. (1999): *Über die Analyse von Beobachtungen in der Ausgleichsrechnung – Äußere und innere Restriktionen*. Schriftenreihe der Institute des Studiengangs Geodäsie und Geoinformatik der Universität Stuttgart, Report Nr. 1999. 6-1, 207-230.
- JURISCH R., KAMPMANN G., LINKE J. (2000): *Über die Analyse von Beobachtungen in der Ausgleichsrechnung*. Zeitschrift für Vermessungswesen, 124, 11, 350-357, 12, 388-395.

- JURISCH R., KAMPMANN G. (2001): *Ein neues Hilfsmittel zur Geometrie-Analyse und Ausreißersuche*. First Internat. Symp. on Robust Statistics and Fuzzy Techniques in Geodesy and GIS, Zürich, IPG-Bericht Nr. 295.
- JURISCH R., KAMPMANN G. (2002): *Teilredundanzen und ihre natürlichen Verallgemeinerungen*. Zeitschrift für Vermessungswesen, 127, 2, 117-123.
- KAMPMANN G., RENNER B. (1999): *Über Modellüberführungen bei der linearen Ausgleichsrechnung*. Allgemeine Vermessungsnachrichten, 106, 2, 42-52.
- KAMPMANN G., RENNER B. (2000): *Numerische Beispiele zur Bearbeitung latenter Bedingungen und zur Interpretation von Mehrfachbeobachtungen in der Ausgleichsrechnung*. Zeitschrift für Vermessungswesen, 125, 6, 190-197.
- KAMPMANN G., KRAUSE B. (2000): *Über Zusammenhänge von balancierter Ausgleichsrechnung mit dem Gravitationsgesetz*. Zeitschrift für Vermessungswesen, 125, 10, 352-357.
- KAMPSHOFF S., BENNING W. (2002): *Integrierte Verarbeitung der Daten des Liegenschaftskatasters einschließlich Homogenisierung*. Zeitschrift für Vermessungswesen, 127, 1, 9-18.
- KLEUSBERG A., KLAEDTKE H.-G. (1999a): *Accuracy assessment of a digital height model derived from airborne synthetic aperture radar measurements*. In: FRITSCH D., SPILLER R. (eds.): Photogrammetrische Woche 99, Wichmann Verlag, Heidelberg, 139-143.
- KLEUSBERG A., KLAEDTKE H.-G. (1999b): *Zur Genauigkeit von Digitalen Höhenmodellen aus Radarbefliegungen*. Allgemeine Vermessungsnachrichten, 106, 6, 202-207.
- KIEFNER M. (2001): *Einfluss von Bildkompressionsverfahren auf die Qualität der digitalen Punktübertragung*. Deutsche Geodätische Kommission, Reihe C, Heft Nr. 531, München.
- KLONOWSKI J. (1999): *Segmentierung und Interpretation digitaler Bilder mit Markov-Zufallsfeldern*. Deutsche Geodätische Kommission, Reihe C, Heft-Nr. 492, München.
- KOCH A., HEIPKE C. (2001): *Quality Assessment of Digital Surface Models derived from the Shuttle Radar Topography Mission (SRTM)*. Internat. Geoscience and Remote Sensing Symposium, Sydney, Australia.
- KOCH A., HEIPKE C., LOHMANN P. (2002): *Bewertung von SRTM Digitalen Geländemodellen – Methodik und Ergebnisse*. Photogrammetrie, Fernerkundung, Geoinformation, 6, 389-398.
- KOCH K.-R. (1999a): *Parameter Estimation and Hypothesis Testing in Linear Models. Second, updated and enlarged Edition*. 333 p., Springer-Verlag, Berlin, Heidelberg.
- KOCH K.-R. (1999b): *Grundprinzipien der Bayes-Statistik*. Schriftenreihe der Institute des Studiengangs Geodäsie und Geoinformatik der Universität Stuttgart, Report Nr. 1999. 6-1, 253-259.
- KOCH K.-R. (2000a): *Einführung in die Bayes-Statistik*. 225 S., Springer-Verlag, Berlin, Heidelberg.
- KOCH K.-R. (2000b): *Beispiele zur Parameterschätzung, zur Festlegung von Konfidenzregionen und zur Hypothesenprüfung*. Mitteilungen aus den Geodätischen Instituten der Universität Bonn, Nr. 87.
- KOCH K.-R. (2000c): *Numerische Verfahren in der Bayes-Statistik*. Zeitschrift für Vermessungswesen, 125, 12, 408-414.
- KOCH K.-R. (2002): *Räumliche Helmert-Transformation variabler Koordinaten im Gauß-Helmert- und im Gauß-Markoff-Modell*. Zeitschrift für Vermessungswesen, 127, 3, 147-152.
- KOCH K.-R., KUSCHE J. (2002): *Regularization of geopotential determination from satellite data by variance components*. Journal of Geodesy, 76, 259-268.
- KUHLMANN H. (2001): *Importance of Autocorrelation for Parameter Estimation in Regression Models*. Proceedings of the 10th FIG International Symposium on Deformation Measurements, Orange, California.
- KULSCHEWSKI K. (1999): *Modellierung von Unsicherheiten mit Bayes-Netzen zur qualitativen Gebäudeerkennung und -rekonstruktion*. Dissertation. Shaker Verlag, Aachen.
- KUTTERER H. (1999): *On the sensitivity of the results of least-squares adjustment concerning the stochastic model*. Journal of Geodesy, 73, 350-361.
- KUTTERER H., SCHÖN S. (1999): *Statistische Analyse quadratischer Formen – der Determinantenansatz*. Allgemeine Vermessungsnachrichten, 106, 10, 322-330.
- LENK U. (2001): *Schnellere Multiplikation großer Matrizen durch Verringerung der Speicherzugriffe und ihr Einsatz in der Ausgleichsrechnung*. Zeitschrift für Vermessungswesen, 126, 4, 201-207.
- LENZMANN E., LENZMANN L. (2001): *Zur Bestimmung eindeutiger Transformationsparameter*. Zeitschrift für Vermessungswesen, 126, 3, 138-142 (contrary arguments by J. REINKING, K.-R. KOCH, and reply by LENZMANN and LENZMANN in Zeitschrift für Vermessungswesen, 126, 5, 295-299).
- LENZMANN L. (2001): *Zur Bestimmung der Transformationsparameter nach der Methode der kleinsten Quadrate*. Zeitschrift für Vermessungswesen 126, 6, 361-365.
- MAAS H.-G. (2001): *Least-squares matching techniques for the assessment of the planimetric quality of airborne laser-scanning data*. 3rd Internat. Symp. on Mobile Mapping Technology, Cairo.
- MEIER S. (1999): *Vom Punktlagefehler zum Qualitätsmodell*. Schriftenreihe der Institute des Studiengangs Geodäsie und Geoinformatik der Universität Stuttgart, Report Nr. 1999. 6-2, 323-329.
- MEIER S. (2000): *Zur Qualität snakes-approximierter Höhenprofile mit Diskontinuitäten*. Photogrammetrie, Fernerkundung, Geoinformation, 6, 399-409.
- MEIER S. (2003): *Zur K-Frage: Kompressionsraten der schnellen Wavelettransformation aus statistischer Sicht*. Zeitschrift für Vermessungswesen, 128, 1, 31-39.
- MENZ J. (1999): *Forschungsergebnisse zur Geomodellierung und ihre Bedeutung*. Math. Geologie, 4, 19-30.
- MENZ J. (2000): *Angewandte Geostatistik in Bergbau, Geologie, Geophysik, Geodäsie und Umweltschutz*. Math. Geologie, 5.
- MENZ J., KOLESNIKOV N. (2002): *Bestimmung der Parameter der Kovarianzfunktion aus den Differenzen zweier Vorhersageverfahren*. Math. Geologie, 7.
- MENZ J., KNOSPE S. (2002): *Lokale Bestimmung des Geoids aus terrestrischen Gradiometermessungen unter Nutzung geostatistischer Methoden*. Zeitschrift für Vermessungswesen, 127, 5 321-332.
- MÜLLER J., BENNING W. (1999): *Homogenisierung dreidimensionaler Szenarien nach der Methode der kleinsten Quadrate*. Allgemeine Vermessungsnachrichten, 106, 10, 337-342.

- NIEMEIER W. (2002): *Ausgleichsrechnung. Eine Einführung für Studierende und Praktiker des Vermessungs- und Geoinformationswesens*. 407 S., Walter de Gruyter, Berlin, New York.
- NITSCHKE H. (2002): *Zur Bestimmung geometrischer Parameter von Industrierobotern*. Deutsche Geodätische Kommission, Reihe C, Heft Nr. 547, München.
- PENZKOFER M., BRUNNER K., FISCHER J., REINHARDT W. (2001): *Untersuchungen zur Genauigkeitsanalyse von Alpenvereinskarten*. Zeitschrift für Vermessungswesen, 126, 1, 5-10.
- REICH M. (2001): *Validierung von X-SAR SRTM Höhendaten mit Laserhöhen- und Laserintensitätsdaten*. Final Report, Shuttle Radar Topography Mission (SRTM).
- ROSCHLAUB R. (1999): *Klassifikation und Interpolation mittels affin invarianter Voronoidiagramme auf der Basis eines Wahrscheinlichkeitsmaßes in großmaßstäbigen Informationssystemen*. Deutsche Geodätische Kommission, Reihe C, Heft Nr. 509, München.
- SCHLICHTING R. (1999): *Zur Genauigkeit und Optimierung des Vorwärtseinschnitts bei Deformationsmessungen*. Zeitschrift für Vermessungswesen, 124, 7, 216-221.
- SCHMIDT M. (1999): *Approximate solution of normal equations by eigenvalue decomposition*. Journal of Geodesy, 73, 109-117.
- SCHMIDT M. (2000): *Wavelet analysis of stochastic signals*. IERS Technical Note No. 28, 65-71.
- SCHMIDT M., SCHUH H. (2000): *Abilities of wavelet analysis for investigating short period variations of Earth rotation*. IERS Technical Note No. 28, 73-80.
- SCHMIDT M. (2001a): *Wavelet-Analyse von Erdrotationsschwankungen*. Zeitschrift für Vermessungswesen, 126, 94-100.
- SCHMIDT M. (2001b): *Ein Beitrag zur zweidimensionalen Wavelet-Analyse von Zufallsprozessen*. Zeitschrift für Vermessungswesen, 126, 270-275. .
- SCHMIDT M. (2001c): *Grundprinzipien der Wavelet-Analyse und Anwendungen in der Geodäsie*. Habilitationsschrift. Shaker Verlag, Aachen.
- SCHMIDT M. (2002): *Wavelet-Analyse von Zeitreihen*. Deutsche Geodätische Kommission, Reihe A, Heft Nr. 118, 46-56, München.
- SCHWIEGER V. (1999): *Ein Elementarfehlermodell für GPS-Überwachungsmessungen – Konstruktion und Bedeutung interepochaler Korrelationen*. Wissenschaftliche Arbeiten der Fachrichtung Vermessungswesen der Universität Hannover, Nr. 231.
- SCHWIEGER V. (2001): *Zur Konstruktion synthetischer Kovarianzmatrizen*. Zeitschrift für Vermessungswesen, 126, 143-150.
- SEESTER M. (2000): *Automatische Generalisierung mittels Ausgleichung*. Mitteilungen des Bundesamtes für Kartographie und Geodäsie, 17, 105-113.
- SEESTER M. (2001a): *Maßstabsabhängige Darstellungen in digitalen räumlichen Datenbeständen (5.2 Verdrängung durch vermittelnde Ausgleichung – das Programm PUSH, 67-80)*. Deutsche Geodätische Kommission, Reihe C, Heft Nr. 544, München.
- SEESTER M. (2001b): *Optimization Approaches for Generalization*. GISRUK– Conference, Cardiff, Wales.
- STEGELMANN V. (2000): *Zuverlässigkeit bei Liegenschaftsvermessungen*. Nachrichten der Niedersächsischen Vermessungs- und Katasterverwaltung, 50(3), 11-16.
- STUBENVOLL R. (2000): *Alongtrack-/Crossover-Verfahren und Spektralanalyse zur Trennung geodätisch-geophysikalischer Signale in Altimeterdaten*. Deutsche Geodätische Kommission, Reihe C, Heft Nr. 524, München.
- WENDT A. (2002): *Gemeinsame Ausgleichung von Laserscannerdaten und digitalen photogrammetrischen Bildern*. Photogrammetrie, Fernerkundung, Geoinformation, 2, 103-110.
- WITTE B., SCHMIDT H. (2000): *Vermessungskunde und Grundlagen der Statistik für das Bauwesen*. 4. Auflage, Konrad Wittwer Verlag, Stuttgart.
- ZEITLER W. (1999): *Simultane Neuausgleichung des globalen 3D-Mars-Netzes*. Deutsche Geodätische Kommission, Reihe C, Heft Nr. 511, München.

Non-stochastic methods of data evaluation

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Introduction

The evaluation and analysis of geodetic data acts as an interface between the observation techniques and the respective mathematical-physical models. Although the requirements from the applicational side are manifold, the data analysis techniques can be classified from a methodological point of view. Classically, it is distinguished between deterministic and stochastic signals. Deterministic signals can be represented by completely specified mathematical functions. Here, uncertainty either plays no role or remains as noise. Stochastic signals are defined as random variables depending on one or more variables. They refer to the laws of probability and are not exactly predictable.

Typically, there are more types of uncertainty in geodetic data and models than just randomness. In these cases dedicated data analysis techniques have to be considered since deterministic approaches are incapable to qualify uncertainty and the use of stochastic methods is too restrictive. This contribution is based on the assumption that the data are not stochastic, at least not at first glance. It has two parts. The first part is concerned with deterministic signal analysis as defined above. In the second part non-random uncertainty of the data or of the model is explicitly taken into account using interval mathematics, fuzzy theory and artificial neural networks.

Deterministic signal analysis

The application of Fourier techniques is the classical way to analyse deterministic signals. However, if the signals are characterized by time-varying amplitudes and/or frequencies, the Fourier transform is inappropriate, since exponential basis functions cannot detect local signal structures. Recently the wavelet transform has become a very promising tool for investigating geodetic observation series. Due to the localizing feature of a wavelet function the wavelet transform analyses a signal namely in a local area of variable size in the so-called phase space spanned by time and frequency. Thus, the most important property of the wavelet transform is the detection of time-variable signal features by adapting an appropriate wavelet function to the signal to be analysed. The habilitation thesis of SCHMIDT (2001a) presents a detailed overview about the basic principles of wavelet theory in one and more dimensions. The theoretical considerations are supported by numerous geodetic applications.

In general, a wavelet function is defined as a function with zero mean either compactly supported or quasi-compactly supported with respect to the time domain. The quasi-com-

pactly supported Morlet wavelet is characterized by the smallest possible time-frequency window in the phase space, i.e. the highest possible resolution in both time and frequency. This gives reason why this wavelet function is often used in geodetic and geophysical applications. SCHMIDT (2001b) uses the Morlet wavelet transform to study variations of Earth rotation data, e.g. to analyse the Chandler wobble and the annual signal part. SCHMIDT and SCHUH (1999) apply this technique to detect the Free Core Nutation from Very Long Baseline Interferometry results. SCHMIDT and SCHUH (2000) use the Morlet wavelet transform to compare polar motion and length-of-day time series with atmospheric angular momentum time series for the short-period range. ARFA-KABOODVAND et al. (1999) apply wavelet analysis to GPS observations in order to study the variability of Earth rotation data sets in the subdiurnal period range.

Basically the wavelet transform can be used for both signal analysis and signal representation (synthesis). In physical geodesy the latter is very important in the context of gravity field representation. Due to its localizing property in both the space and the frequency domain, the spherical wavelet transform can be used to model regional or even local geodata. FREEDEN (1999) presents a detailed description of spherical wavelet theory for modelling space borne geodata. There is a large number of contributions concerning many different aspects of spherical wavelet theory published by the members of the geomathematics group of the University of Kaiserslautern. Some of these publications are listed in the subsection "Mathematical aspects of geodetic modelling" of section IV of this national report and will not be repeated here. A more general construction principle of wavelets is presented by FREEDEN (2001). In this paper the theory and algorithmic aspects of wavelets are studied in a general separable Hilbert space framework. As an example Legendre wavelets are presented.

BEYER (1999) also treats the aspect of signal representation by means of the wavelet transform in the context of relief-related space curves in hybrid digital terrain models. After finding a suitable parameterization of the space curves data compression methods can be applied to the corresponding wavelet coefficients. Besides the aspect of data compression the wavelet transform can also be used in approximation problems, i.e. the derivatives of the signal can be gained from the wavelet transform in the phase space. BEYER und MEIER (2001) compute the terrain gradient and curvature directly from the coefficients of the wavelet transformed digital terrain model. One-dimensional approximation formulae for terrain profiles are presented considering undesired phase

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shifts as well as examples using the Haar wavelet and the Daubechies-4 wavelet.

The Haar wavelet can be used for edge and line detection in digital image analysis as mentioned by SCHMIDT (2001a). BUSCH (2001) presents two methods for both edge and line detection as well as texture recognition in satellite images. A threshold that is required for edge and line extraction is estimated robustly from the image data.

The principal component analysis (PCA) is a mathematical tool to expand a multivariate data set into a series in basis vectors derived directly from the data. The purpose of this method is the extraction of the main part of the total variance to separate the dominant signal components from the non-dominant. Whereas the Fourier series for example is restricted to sinusoidal processes, PCA can be applied to extract arbitrarily shaped deterministic model parts from the data set. In geodesy PCA is usually applied to space- and time-dependent data sets. Whereas the basis vectors are space-dependent the corresponding series coefficients are purely time-dependent. BOSCH (2001) uses PCA to analyse sea level variations in the pacific derived from satellite altimetry. This way seasonal variations as well as aperiodic processes like El Niño and La Niña are identified. GROTEN et al. (2000) apply PCA to El Niño and La Niña data sets and compare the results with the main characteristics of Earth rotation, namely polar motion and length-of-day variations. SCHMIDT (1999) uses PCA to derive an approximate solution of normal equations. The approximation method is based on the decomposition of the covariance matrix of the observations, calculated in a pre-processing step, into a system of eigenvalues and eigenvectors. The consideration of merely the dominant eigenvalues yields the desired approximation.

Finally, two rather new mathematical methods for deterministic signal analysis are presented: first the global optimization method and then the maximum correlation adjustment. If the identification of deterministic periodic signals in time series is treated as an adjustment problem the solution strategy depends on the available prior information on the signal frequency. In case of unknown frequencies, the functional model is inevitably nonlinear in the parameters. Hence, the sum of squared residuals which is minimised in LSE may have a multitude of local minima in addition to the global minimum. As typical solvers for nonlinear equations work locally, the correctness of the obtained solution depends on particular initial values. MAUTZ (2001) proposed a strategy which allows to overcome this problem. It is based on heuristic global optimization techniques using varying initial values. Maximum correlation adjustment (MCA) is based on the quantitative comparison of data and model by means of their correlation coefficient (NEITZEL, 2001). A set of solutions is obtained by maximizing the correlation coefficient. In geometric deformation analysis the Helmert transformation is one of the MCA solutions.

Interval mathematics and fuzzy data analysis

In geodetic practice typically both the data and the model are uncertain up to certain degree due to several causes. In

this section, random variability (stochasticity) and imprecision are considered as data uncertainty components. Stochasticity is caused by uncontrollable effects during the observation process. Imprecision expresses remaining systematic deviations between the observations and the model due to imperfect knowledge or just for practical reasons. The theory of stochastics offers a variety of mathematical methods to deal with stochasticity whereas interval mathematics and fuzzy theory supply adequate mathematical approaches to handle imprecision (KUTTERER, 2001a, 2002a). Imprecision can be considered in data analysis in various ways. First, it has to be modelled observation by observation in mathematical terms. Then, the imprecise observations have to be composed to an imprecise observation vector. Afterwards, the output data is derived by some calculus. Eventually in this step, the imprecision of the input data has to be taken into account for the derivation of the output data. Finally, the imprecision of the output data has to be quantified.

Imprecision can be taken into account either by intervals or fuzzy numbers. An interval is defined by its lower and its upper bound or, equivalently, by its mean point and its radius. The radius of the interval is a proper measure of imprecision. A fuzzy number is typically defined by its membership function which is controlled by a mean point parameter and a spread parameter. Fuzzy numbers can be understood as generalized intervals. Imprecision measures based on fuzzy numbers are proportional to the spreads (KUTTERER, 2002a). The definition of vectors is unique in case of intervals whereas in fuzzy theory there are several ways like, e.g., according to the minimum rule or based on quadratic forms (KUTTERER, 2001c, 2002a).

Least-squares (LS) adjustment is a typical technique in geodetic data analysis. The case of observation intervals and their impact on the LS estimator (LSE) was already discussed by KUTTERER (1994). This work has been continued by SCHÖN and KUTTERER (2001a, b, 2002) in order to solve two problems. First, in geodetic practice imprecision needs to be quantified by numbers. Second, the impact of observation imprecision on the estimated parameters can be minimized using mathematical optimization techniques. Both aspects are studied in detail by SCHÖN (2003).

KUTTERER (2001c) discusses two different ways to introduce imprecision to the LSE in a Gauss-Markov model based on fuzzy theory. The first one is the *fuzzy-extended LSE* where the imprecise observations vector is inserted into a consistent extension of the LSE. The mean point of the fuzzy-extended LSE is equivalent to the classical LSE. Its spreads quantify the imprecision in addition to the variance-covariance matrix which represents stochastic dispersion. The second one is based on the maximum similarity principle and leads to the *fuzzy LSE in the strict sense* and to the *hybrid fuzzy LS approximation*.

In geodetic practice neither the stochastic approach nor the interval or fuzzy approach are adequate to jointly handle stochasticity and imprecision. For this reason the discussion of the fuzzy LSE has been extended to confidence regions and hypothesis tests for stochastic and imprecise data. KUTTERER (2002a) outlines the concepts for both problems

and derives some general results. The main idea is to apply the extension principle of fuzzy theory to the respective mathematical relations. The derivation of fuzzy-extended confidence regions to the resolution of GPS phase ambiguity parameters was studied in KUTTERER (2001b, 2002b). Statistical hypothesis tests for imprecise data are derived in KUTTERER (2003). A particular kind of model imprecision was considered by KUTTERER (1999) who derived the impact of interval weight matrices on the results of least-squares adjustments.

Fuzzy systems and artificial neural networks

In many applications of control theory and of decision theory it is either expensive or just impossible to acquire complete and precise information on all relevant parameters and relations. Hence, the need for moderate complex but adequate models leads to the development of fuzzy systems which are based on fuzzy logic. Fuzzy systems consist of four components: an input component, an inference component, an output component and a feedback connection from the output to the input. The input component comprises an interface which allows to fuzzify real input data by means of linguistic variables such as "length" with the fuzzy states "short", "medium", "long". The inference component consists of a fuzzy rule base and a method for the aggregation of the resulting fuzzy set. The output component yields real parameters which are derived from the fuzzy result by a defuzzification method.

Fuzzy models were used successfully by HEINE (1999, 2001a, b) for the modelling of deformation processes. LEINEN (2001) studied the On-The-Fly resolution of GPS phase ambiguities as a multi-attribute decision making process in order to assess the importance of some evidence pro or contra a particular candidate solution. JOOS (2001) presented the "egg-yolk" approach which allows to model fuzzy transition zones between spatial objects in GIS such as meadows and forests. An adaptive network fuzzy inference system (ANFIS) was studied by AKYILMAZ and KUTTERER (2003) for the short-term prediction of Earth orientation parameters.

The artificial neural networks (ANN) represent an independent methodology to handle various types of uncertainty. They have been developed in order to imitate human thinking. They are composed of a large number of simple processors (neurons) that are massively connected and operate simultaneously. ANN are trained based on examples what is called machine learning. During the training process individual weights are assigned to the neurons. Some work has been done on the application of ANN to geodetic problems. SCHUH et al. (2002) studied the prediction of Earth orientation parameters. HEINE (1999) and NIEMEIER and MIIMA (2001) considered the modelling of deformation processes. Note that both fuzzy systems and ANN are solely mathematical representations of the underlying physical processes. They offer easy-to-handle best-fit solutions but they are inadequate for physical interpretation.

References

- AKYILMAZ O., KUTTERER H.: *Prediction of Earth orientation parameters by fuzzy inference systems*. Report No. 75, DGFI, München, 2003.
- ARFA-KABOODVAND K., GROTEN E., ZAVOTI J., VARGA P.: *Stochastische und deterministische Analyse sowie Modellierung der Erdrotation mit Schwerpunkt: Polschwankung und DUTI (= LOD), basierend auf GPS-Daten*. In: Schneider M.: 3. DFG-Rundgespräch zum Thema Bezugssysteme. Mitteilungen des Bundesamtes für Kartographie und Geodäsie, Band 5, 126-133, 1999.
- BEYER G.: *Representation and Wavelet Transformation of Relief-Related Space Curves*. IARPS, Vol. 32, Part 3-2W5, 49-54, 1999.
- BEYER G., MEIER S.: *Geländeneigung und -wölbung aus Waveletkoeffizienten*. Approximationsformeln für Profile. Zeitschrift für Vermessungswesen, 126, 23-33, 2001.
- BOSCH W.: *EOF-Analysen der Meeresspiegel-Schwankungen im Pazifik*. Zeitschrift für Vermessungswesen, 126, 74-81, 2001.
- BUSCH A.: *Schätzung von Schwellwerten für die automatische Bildauswertung*. Zeitschrift für Vermessungswesen, 126, 82-87, 2001.
- CAROSIO A., KUTTERER H. (EDS.): *Proceedings of the First International Symposium on Robust Statistics and Fuzzy Techniques in Geodesy and GIS*. Swiss Federal Institute of Technology Zurich, Institute of Geodesy and Photogrammetry – Report No. 295, 2001.
- FREEDEN W.: *Multiscale Modelling of Spaceborne Geodata*. Teubner, 1999.
- FREEDEN W.: *A General Construction Principle of Wavelets*. In: Banday A.J., Zaroubi S., Bartelmann M. (Eds.): *Proceedings of the MPA/ESO/MPE Workshop 2000 'Mining the Sky'*, 53-70, Springer, 2001.
- GROTEN E., FENOGLIO-MARC L., WANG L.: *El Niño (1997) – main characteristics and interannual Earth rotation variability*. Allgemeine Vermessungs-Nachrichten, 4, 140-146, 2000.
- HEINE K.: *Beschreibung von Deformationsprozessen durch Volterra- und Fuzzy-Modelle sowie Neuronale Netze*. Deutsche Geodätische Kommission, Series C, Nr. 516, München, 1999.
- HEINE K.: *Potential applications of fuzzy methods in geodetic fields*. In: Carosio A., Kutterer H. (Eds.), 87-94, 2001a.
- HEINE K.: *Using Artificial Neural Networks and Fuzzy Technology for Geodetical Data Analysis*. In: CD-ROM Proceeding of the IAG 2001 Scientific Assembly, Budapest, 02.09.-07.09.01, 2001b.
- JOOS G.: *Modeling Uncertainty in GIS*. In: Carosio A., Kutterer H. (Eds.), 133-138, 2001.
- KUTTERER H.: *Intervallmathematische Behandlung endlicher Unschärfen linearer Ausgleichungsmodelle*. Deutsche Geodätische Kommission, Series C, Nr. 423, München, 1994.
- KUTTERER H.: *On the sensitivity of the results of least-squares adjustments concerning the stochastic model*. Journal of Geodesy (1999) 73: 350-361, 1999.
- KUTTERER H.: *Uncertainty assessment in geodetic data analysis*. In: Carosio A., Kutterer H. (Eds.), 7-12, 2001a.
- KUTTERER H.: *An imprecise search space for GPS phase ambiguity parameter*. In: Carosio A., Kutterer H. (Eds.), 215-220, 2001b.

- KUTTERER H.: *Some considerations on Fuzzy Least-Squares*. In: Sideris, M. (Ed.): Gravity, Geoid and Geodynamics 2000. Springer, Berlin Heidelberg, 73-78, 2001c.
- KUTTERER H.: *Zum Umgang mit Ungewissheit in der Geodäsie - Bausteine für eine neue Fehlertheorie*. Deutsche Geodätische Kommission, Series C, Nr. 553, München, 2002a.
- KUTTERER H.: *Joint treatment of random variability and imprecision in GPS data analysis*. Journal of Global Positioning Systems, Vol. 1, No. 2:96-105, 2002b.
- KUTTERER H.: *Statistical hypothesis tests in case of imprecise data*. In: Sanso F.: Proceedings of the 5th Hotine-Marussi Symposium, Springer, Berlin, accepted for publication, 2003.
- LEINEN S. (2001): *Fuzzy-Logic Based GPS On-The-Fly Ambiguity Search*. In: Carosio A., Kutterer H. (Eds.) 209-214, 2001.
- MAUTZ R.: *Zur Lösung nichtlinearer Ausgleichungsprobleme bei der Bestimmung von Frequenzen in Zeitreihen*. Deutsche Geodätische Kommission, Series C, Nr. 532, München, 2001.
- NEITZEL F. (2001): *Maximum Correlation Adjustment in Geometrical Deformation Analysis*. In: Carosio A., Kutterer H. (Eds.) 123-132, 2001.
- NIEMEIER W., MIIMA J.B. (2001): *A Neural Network Approach for Modelling Geodetic Deformations*. In: Carosio A., Kutterer H. (Eds.), 111-116, 2001.
- SCHMIDT M.: *Approximate solution of normal equations by eigenvalue decomposition*. Journal of Geodesy, 73, 109-117, 1999.
- SCHMIDT M.: *Grundprinzipien der Wavelet-Theorie und Anwendungen in der Geodäsie*. Habilitation thesis, Shaker, Aachen, 2001a.
- SCHMIDT M.: *Wavelet-Analyse von Erdrotationsschwankungen*. Zeitschrift für Vermessungswesen, 126, 94-100, 2001b.
- SCHMIDT M., SCHUH H.: *Wavelet-Analyse der mit VLBI beobachteten Nutationsreihen*. Zeitschrift für Vermessungswesen, 124, 24-30, 1999.
- SCHMIDT M., SCHUH H.: *Abilities of Wavelet Analysis for Investigating Short-period Variations of Earth Rotation*. IERS Technical Note 28, 73-80, 2000.
- SCHÖN S.: *Analyse und Optimierung geodätischer Netze unter besonderer Berücksichtigung des Intervallansatzes*. Ph.D. Thesis, Summer 2003.
- SCHÖN S., KUTTERER H.: *Interval-based description of measurement uncertainties and network optimization*. In: Carosio A., Kutterer H. (Eds.), 41-46, 2001a.
- SCHÖN, S., KUTTERER H.: *Optimal design of geodetic monitoring networks by means of interval mathematics*. In: Whitacker C. (Ed.): Proceedings of the 10th FIG International Symposium on Deformation Measurements, 19.03.-22.03.2001, Orange, California, U.S.A., S. 362-371, 2001b.
- SCHÖN S., KUTTERER H.: *Network optimization with respect to systematic errors*. In: Ādám J., Schwarz K.-P. (Eds.): Vistas for Geodesy in the New Millenium. IAG Symposia, Vol. 125, Springer, 329-334, 2002.
- SCHUH H., ULRICH M., EGGER D., MÜLLER J., SCHWEGMANN W. (2002): *Prediction of Earth Orientation Parameters by Artificial Neural Networks*, Journal of Geodesy, Vol. 76 (5), 247-258, 2002.

SECTION V
GEODYNAMICS

Geodynamics

– Overview and highlights –

H. DREWES¹

Overview

The report on the activities of German scientists and institutions in geodynamics research during the time period 1999 to 2003 shall be divided according to the structure of IAG Section V:

- Crustal deformation (Commission XIV),
- Tidal and non-tidal gravity field variations (Commission V Earth Tides and IAG/IAPSO Joint Working Group on Geodetic Effects of Non-Tidal Oceanic Processes),
- Sea level and ice sheets (Special Commission 8),
- Earth rotation (International Earth Rotation Service, IERS).

German scientist were strongly involved in all of these components of Section V. They contributed to the observation of geodynamic phenomena, performed data analyses and interpretations, and participated in the organization of symposia, workshops and meetings on these topics. They accepted several positions in the scientific bodies of section V.

In Commission XIV, BERND RICHTER acted as a Vice-president. The Symposium on Recent Crustal Deformations in South America and Surrounding Areas was organized with assistance of several German co-conveners. Projects were performed in the Sub-commissions for Antarctica, Central- and South America, Europe (CEI and WEGENER), and Asia (APSG).

In Commission V, German scientists were active in all the present Working Groups (WG): WG4 "Calibration of Gravimeters", WG5 "Global Gravity Monitoring Network" (Chair BERND RICHTER), WG6 "Earth Tides in Geodetic Space Techniques (Chair HARALD SCHUH), WG7 "Analysis of Environmental Data" (Chair GERHARD JENTSCH).

The Special Commission 8 is co-chaired by REINHARD DIETRICH. The Institute of Planetary Geodesy, Dresden, is maintaining the Data Base of the Epoch GPS Campaigns of ICSU's Scientific Committee on Antarctic Research (SCAR).

The Central Bureau of the IERS is driven since January 2001 by BKG, Frankfurt/Main, its Director is BERND RICHTER. Several German individuals and groups are involved in the specific components of the IERS, in particular in the Combination Research Centers with the Analysis Coordinator

MARKUS ROTHACHER, and as ITRF Combination Centre at DGFI.

Highlights

The most important results with respect to *crustal deformation* research were the improved global plate kinematics and inter-plate deformation models (APKIM) as well as the regional observation and modelling in Europe (CERGOP, WEGENER), Asia (CATS, GEODYSSEA), South America (CASA, SAGA) and Antarctica (SCAR). Detailed features of continuous surface deformation and earthquake induced abrupt displacements have been monitored. The geodetic space techniques used for monitoring the position changes have intensively been analysed in order to improve the accuracy and reliability. Parameter estimation approaches and models have been studied for optimum adaption to the specific problems.

Investigations on *tidal and non-tidal gravity field variations* concentrated on records with tidal and superconducting gravimeters as well as their modelling and interpretation. The instruments were installed in Germany and South Africa. The modelling included improved tidal models, oceanic loading and local effect. Environmental parameters (atmospheric, hydrologic) and geophysical processes (tectonics, earthquakes) were subject of detailed interpretation.

Investigations on *sea level and ice sheets* may be highlighted by the activities on monitoring secular and periodic sea-level changes using tide gauge records and satellite altimetry, as well as the determination of ice sheet topography and its variations including the ice-ocean-atmosphere-solid Earth mass balance. Great efforts have been made to reduce the tide gauge records by vertical crustal movements obtained from GPS observations. Altimeter data were intensively analysed for calibrating and combining them with different missions and with other techniques. Satellite altimetry and SAR interferometry data were used for monitoring ice dynamics in various regions in Antarctica.

Earth rotation has been investigated in theory, by data analysis and for interpretation. Nutation models were set up and analysed using Newtonian mechanics and Einstein's theory of relativity. The major dynamic processes in the Earth's system (atmosphere, hydrosphere, solid Earth) were included. Processing of VLBI, GPS and SLR data provided improved and regular time series of Earth rotation para-

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meters. Several laser gyroscopes were investigated to obtain a new quality of data in local inertial systems, the most precise one being installed at Wettzell fundamental station. The interpretation of time series of Earth rotation parameters included the excitation of Chandler and annual periods down to diurnal effects.

Conclusion

The geodynamics research has been continued in Germany by theoretical, experimental and interpretation studies. Some fundamental achievements have been gained. The financial support of the German federal and states' governmental agencies and ministries as well as the Deutsche Forschungsgemeinschaft (DFG) is gratefully acknowledged.

Crustal Deformation

W. AUGATH¹

General trend

The determination of crustal deformation takes profit from the general progress in the field of reference systems and their realisation. Due to the fact that modern reference systems are realised on a kinematic basis with the parameters x, y, z and the corresponding velocities, these results can also be used for the determination of crustal deformation.

In the last period 1999-2003 further progress have been reached in:

- developing global geodetic models of kinematics (e.g. APKIM-model of DREWES (1999) and ANGERMANN, DREWES, 2000) including the border zones (HEIDBACH (2000), KLOTZ, 2000),
- measurements, especially with global space techniques like SLR, VLBI and GPS (see section I or e.g. ANGERMANN et al., 2002, CAMPBELL et al., 2002, TESMER, 2000), SEEMÜLLER et al., 2002),
- geodetic infrastructure realised with fundamental stations, the IGS and his continental and national densifications.

Classic methods of measurement have mostly been replaced by space-based techniques and are only used today on a local basis or in areas where satellite techniques are not available. In the field of vertical deformation the precise levelling remains important but mainly as precise representation of the geometry 50..100 years ago (e.g. SACHER et al., 2000). On the other hand repeated absolute gravity measurements are increasingly in use for the determination of height changes (e.g. TORGE et al., 1999).

Meanwhile the high density of permanent geodetic infrastructure allows the connection of all regional and local projects and campaigns to the ITRS/ ITRF. This leads not only to a higher quality of the results without additional costs. The possibility of the determination of deformations on a local, regional as well as on a global level with the same data set leads to advantages in the methodology, too (e.g. the local NNSAT-project, AUGATH et al., 2001).

The level of communication also allows the monitoring of relevant points up to real time. Last but not least the level of interpretation of geodetic results takes profit from the higher quality of the results in general and especially from longer time series.

Projects and campaigns

The projects and campaigns in the last period are spread over the whole world and continue former activities. Due to the technical progress and the additional observation period

of four years, the results are more reliable so that their interpretation come to the fore.

On the global level e.g. GRAFAREND, ARDALAN (2001) determine significant changes of fundamental geodetic parameters of the World Geodetic Datum 2000. KRUMM, GRAFAREND (2002) define datum-free deformation measures and analyse the co-ordinates of ITRF networks. Fennoscandia (GÖBELL et al., 1999) and Southeast Alaska (BÖLLING et al., 2001) are used as test areas with post glacial rebound effects and actual geodetic measurements for the explanation of measured land uplift rates with geophysical models.

The stability of the European plate leads to a concentration of the activities on border zones and areas outside the so-called “stable part” of Europe. In Germany two areas remain, the North Sea Coast where the height component is of special interest (AUGATH et al., 2001) with special investigations including GPS signal validation and the integration of Water Vapour Radiometer measurements. Horizontal movements are being investigated in the Rheingraben (HECK, 2000) including the integration of classical and GPS-observations. The determination of height changes also is the main focus of the Alp-traverse (e.g. SCHMITT, LEMP, 2001) and MARCHESINI, SCHMITT, 1999). The interesting areas of Eastern Europe are being investigated within the CERGOP-activities. This project combines permanent and epoch-based GPS observations in order to determine the velocity field and present day tectonic deformations in the Central European area. A uniform solution combining all previous solutions was derived (BECKER et al., 2002a and BECKER et al., 2002b). Studies on GPS data analysis and the integration of additional sensors both for the CERGOP and the WEGENER project were analysed in (BECKER, BRUYINX, FRENANDEZ, 2002) and BECKER, HÄFELE, PESEC, 2002).

A special focus on Romania is given by (DINTER, SCHMITT, 2000 and DINTER et al., 2001).

The main activities around Europe are concentrated on border zones: e.g. Island (VÖLKSEN, 2000), Adriatic Sea (ALTINER et al., 1999), the West Hellenic and Calabrian Arc (KANIUTH et al., 1999) and various areas in Turkey (ALTINER et al. (1999).

Asia constitutes an important area of investigations with the projects CATS and GEODYSSSEA.

New results from the CATS (Central Asian Tectonic Sciences) project confirm the current high rates of tectonic deformation far north of the India-Eurasia suture zone and quantify the partitioning of deformation within the seismically active Tien Shan and Northern Pamirs (REIGBER et al., 2001).

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Regional deformation rates have increased considerably within the study area since the onset of shortening 20-25 million years ago. The virtually undeformed Tarim block rotates with respect to stable Eurasia. There are plans to extend the existing network to other tectonically active areas of the Eurasian plate.

GPS-observed displacement vectors derived in the framework of the GEODYSSEA network confirmed that Sundablock constitutes a stable tectonic block moving approximately east with respect to Eurasia at a velocity of 12 ± 3 mm/yr (MICHEL et al., 2001). No significant motion has been detected along the northern boundary to South China.

In Thailand and Malaysia a combined network for national control network purposes as well as for kinematics was realized as densification of GEODYSSEA (BECKER et al., 2000).

South America is another important area of investigations due to the activities of DGFI and GFZ.

The international Central and South America Geodynamics project CASA supervises the border zones between the Caribbean and South American plate with GPS (Drewes, 2002). Within this area the behaviour of selected reference stations are investigated, too (KANIUTH et al., 2002).

The results of the SAGA (South American Geodynamic Activities) network contribute to a better understanding of the earthquake deformation cycle as well as to a better understanding of mountain building processes (KLOTZ et al., 2001). The present-day deformation of this area is dominated by transient effects related to subduction earthquakes. Most of the transient deformation can be explained by inter-seismic, co-seismic, and post-seismic phases of interplate thrust earthquakes. The area of the great 1960 Mw 9.5 Chile earthquakes shows a pronounced post-seismic deformation 40 years after the event and a significant change in the displacement field with time.

An additional area of scientific research is Antarctica. DIETRICH et al. (2001) report about the realisation of the ITRF co-ordinates and velocities from repeated GPS-campaigns (SCAR project 1995-1998).

Most of the reports are based on GPS-measurements which meanwhile have reached an excellent performance especially with permanent observations.

The activities for modern kinematic height networks, as proposed in the European EVS 2000-project (AUGATH et al., 2002), include not only repeated national levellings and the results of GPS-permanent stations. In addition precise gravity measurements and extractions from tide gauge observations are included, too, with the goal of a higher reliability of the results.

References

- ALTINER Y.: *Analytical Surface Deformation Theory for the Detection of the Earth's Crust Movements*; Springer-Verlag, Berlin, Heidelberg, London, Milan, Paris, Hong Kong, New York, Tokyo, 1999.
- ALTINER Y.: *The contribution of GPS data to the detection of the Earth's crust deformations illustrated by GPS campaigns in the Adria region*; Geophys. J. Int. (2001) 145, 550-559.
- ALTINER Y., AYAN T., CELIK R. N., DENIZ R., ERGÜN M., KAHVECI M., LENK O., OCAK M., SALK M., SEEGER H., TÜRKEZER A.: *GPS-Measurements in Turkey from 1990 to 1997*; eds. Altan, O., Grundig, L.: Third Turkish-German Joint Geodetic Days, Istanbul, June 1-4, 1999, pp 799-809.
- ALTINER Y., COLIC K., MEDIC Z., MARJANOVIC M., MEDVED M., MISKOVIC D., PIRIBICEVIC B., RASIC L., SEEGER H., SZOBE M.: *Is the Adriatic Sea a promontory or does it exist as an independent microplate*; In: Reports on Geodesy of the Institute of Geodesy and Geodetic Astronomy, Warsaw 5, 149-157, 1999.
- ANGERMANN D., KLOTZ J., REIGBER CH. (1999): *Space-geodetic Estimation of the Nazca-south America Euler Vector*. In: Earth Planet. Sci. Lett. 171, 329-334.
- ANGERMANN D., KLOTZ J., REIGBER CH. (1999), *Realization of A Terrestrial Reference Frame for Large-scale, GPS-networks*, Abstracts of XXII IUGG General Assembly, Birmingham, A405.
- ANGERMANN D., KLOTZ J., REIGBER CH. (2000), *Geodetic Datum Definition of the Saga Network*, In: *Towards an Integrated Global Geodetic Observing System (IGGOS)*, edited by R. Rummel, H. Drewes, W. Bosch, and H. Hornik, IAG Symposia (120), Springer-Verlag, Berlin, pp. 22-32.
- ANGERMANN D., KLOTZ J., REIGBER CH. (2000): *Realization of A Terrestrial Reference Frame for Large-scale, GPS-networks*, Schwarz, K.P. (Ed.), *Geodesy Beyond 2000 – the Challenges of the First Decade*, International Association of Geodesy Symposia (121), Springer-verlag, Berlin Heidelberg, Pp. 304-309.
- ANGERMANN D., BECKER M. (2000): *Untersuchungen zu Genauigkeit und Systematischen Effekten in Großräumigen GPS-Netzen am Beispiel von GEODYSSEA*, ZfV, No. 3, 2000.
- ANGERMANN D., DREWES H.: *The CTS and plate kinematics*. In: Soffel, M., N. Capitaine (Eds.), *Journées 1999 "Systèmes de référence spatio-temporels" & IX. Lohrmann Kolloquium*, 17-21, Observatoire de Paris, 2000.
- ANGERMANN D., GERSTL M., KELM R., MÜLLER H., SEEMÜLLER W., VEI M.: *Time evolution of an SLR reference frame*, *Advances in Space Research*, Vol. 30/2, 201-206, 2002.
- ANGERMANN D., MÜLLER H., GERSTL M.: *Geocenter Variations Derived From SLR Data to LAGEOS 1 and 2*. In: Adam, J., K.-P. Schwarz (Eds.): *Vistas for Geodesy in the New Millennium*. IAG Symposia, Vol. 125, 30-35, Springer, 2002.
- AUGATH W.: *High-Precision-Positioning Services (HPPS) on their Impact on Geodynamics Proceedings of the 2. Int. Symposium: Geodynamics of the Alps-Adria Area by Means of Terrestrial and Satellite Methods.*; Dubrovnik; Edited by K. Colic and H. Moritz, Zagreb and Graz 1999; P. 49-58.
- AUGATH W., BROSSMANN M., SCHLÜTER W., SUDAU A., WINTER R.: *The Project NNSAT-Precise Height Supervision of Tide Gauges with GPS*. Scrm., Helsinki, Finland, Sept. 2001.

- AUGATH W., ADAM J., BOUCHER C., IHDE J., NIEMEIER W., MARTI U., VAN MIERLO J., MOLENDIJK R., SCHMIDT K., WINTER R.: *EVS 2000, Status and requirements*. Veröffentlichungen der Bayrischen Kommission für die Internationale Erdmessung (BEK), C.H. Beck-Verlag, München, 2001.
- AYHAN M. E., DEMIR C., LENK O., KILICOGLU A., ALTINER Y., BARKA A. A., ERGINTAV S., ÖZENER H.: *Interseismic strain accumulation in the Marmara Sea Region*; Bulletin of the Seismological Society of America, 92, 1, pp 216-229, February 2002.
- BECKER M., ANGERMANN D., NORDIN S., REIGBER CH., REINHART E. (2000): *Das Geschwindigkeitsfeld in Südostasien aus einer kombinierten GPS Lösung der drei GEODYSSSEA Kampagnen von 1994 bis 1998*, ZfV No 3, 2000.
- BECKER M., ANGERMANN D., MICHAEL G. W., WILSON P.: *Seismische Deformation und Krustenextrusion: Interpretation der GEODYSSSEA GPS-Lösungen*; In: Zeitschrift Vermess.-wesen, Stuttgart 125 (2000) 3, S. 80-88.
- BECKER M., REINHART E., CHAKORN BOONPHAKDEE, SANONG MINGSAMON, SAMAD ABU (2000): *Realisation des ITRS in Thailand und Malaysia durch ein kombiniertes Netz für Geokinematik und Landesvermessung*. ZfV 125, No. 3, pp. 95-99, 2000.
- BECKER M., REINHART E., SOEB BIN NORDIN, ANGERMANN D., MICHEL G. W., REIGBER CH.: *Improving the velocity field in South and South-East Asia: The third round of GEODYSSSEA*, Earth Planets Space, Vol. 52 (No. 10), pp. 721-726, 2000.
- BECKER M., BRUYNINX C., FERNANDEZ R. (2002): *Processing and submission guidelines for GPSs solutions to be integrated to a Wegener data base*, Proceedings WEGENER 2002, Athens, Jun 12-14, 2002, NTUA Athens, Greece.
- BECKER M., HAEFELE P., P. PESEC (2002): *First Results of WVR1100 Water Vapor Radiometer Measurements in Graz and the CERGOP-2 Project*. Proceedings WEGENER 2002, Athens, Jun 12-14, 2002, NTUA Athens, Greece.
- BECKER M., CRISTEA E., FIGURSKI M., GERHATOVA L., GRENERCZY G., HEFTY J., KENYERES A., LIWOSZ T., STANGL G. (2002a) *Central European Intraplate Velocities Form Cegm Campaigns*. Egs Xxvii Gen. Ass. Nice, France, April 2002, Geodetic and Geodynamic Programmes of the Cei Symp. G9, Reports on Geodesy, No 1 (58), Warszawa, in Press.
- BECKER M., CAPORALI A., FIGURSKI M., GRENERCZY G., KENYERES A., HEFTY J., MARJANOVIC M., STANGL G. (2002b): *A Regional ITRF Densification by Blending Permanent and Campaign Data – The CEGRN campaigns and the Central European Velocity Field*. In *Vistas for Geodesy in the New Millennium*: IAG scientific assembly, Budapest, Hungary, September 2-7, 2001, Jozsef Adam and Klaus-Peter Schwarz (Eds.), pp 53-58.
- BÖLLING K., HAGEDORN J.M., WOLF D., GRAFAREND E.W. (2001): *Berechnung auflastinduzierter Vertikalbewegungen und Geoidänderungen in Südostalaska mit Hilfe viskoelastischer Erdmodelle*. GeoForschungsZentrum Potsdam, Scientific Report STR 01/01, Potsdam, 2001.
- CAMPBELL J., HAAS R., NOTHNAGEL A. (Eds.) 2002: *Measurements of Vertical Crustal Motion in Europe by VLBI*. Geodetic Institute, University of Bonn, 2002.
- DIETRICH R., DACH R., KUTTERER H., LINDNER K., MAYER M. U.A.: *Ergebnisse der SCAR GPS Kampagnen – ITRF-Koordinaten und Geschwindigkeiten*. In: Dietrich, R. (Ed.): Deutsche Beiträge zu GPS-Kampagnen des Scientific Committee on Antarctic Research (SCAR) 1995-1998. DGK B 310, München, 2001. 11-20.
- DIETRICH R., DACH R., PERLT J., SCHENKE H.W., SCHÖNE T., POHL M., IHDE J., ENGELHARDT G., SEEGER G., MENGE F., VÖLKSEN C., NIEMEIER W., SALBACH H., LINDNER K., KUTTERER H., MAYER M., MILLER H., VEIT A.: *Plate deformations and plate kinematics of Antarctica derived by GPS*; IUGG 99, Birmingham/UK, abstracts, A. 48, 1999.
- DIETRICH R., DACH R., ENGELHARDT G., IHDE J., KORTH W., KUTTERER H., LINDNER K., MAYER M., MENGE F., MILLER H., MÜLLER C., NIEMEIER W., PERLT J., POHL M., SALBACH H., SCHENKE H.-w., SCHÖNE T., SEEGER G., VEIT A., VÖLKSEN C.: *ITRF coordinates and plate velocities from repeated GPS campaigns in Antarctica – an analysis based on different individual solutions*. Journal of Geodesy, 74 (2001), 756 – 766, 2001.
- DINTER G., SCHMITT G.: *Three Dimensional Plate Kinematics in Romania*; Reports on Geodesy 4(45), Warschau, 37-49, 2000.
- DINTER G., NUTTO M., SCHMITT G., SCHMIDT U., GHITAU D., MARCU C.: *Three dimensional deformation analysis with respect to plate kinematics in Romania*; Reports on Geodesy, Warsaw University of Technology, 2 (57), 29-42, 2001.
- DINTER G., SCHMITT G.: *Three dimensional deformation analysis with respect to plate kinematics in Romania*; Natural Hazards, 23 (2001). Kluwer Academic Publishers, 389-406.
- DINTER G., SCHMITT G.: *Monitoring Recent Crustal Movements in the Vrancea-Area in Romania*; In: Altan/Gründig (Ed.): *Proceedings Fourth International Symposium "Turkish-German Joint Geodetic Days"*, 03.-06.04.01, Berlin, Vol. I, 85-93, 2002.
- DREWES H.: *Realisierung des kinematischen terrestrischen Referenzsystems ohne globale Rotation ("no net rotation")*. In: 3. DFG-Rundgespräch zum Thema Bezugssysteme. DGK, Reihe A, Nr. 116, 120-125, München 1999.
- DREWES H.: *Deformations along the Caribbean-South American plate boundary from nine years of repeated GPS observations in the CASA project*. AGU Spring Meeting, Washington, D.C., 29.05.2002.
- GÖBELL S., THOMA M., WOLF D., GRAFAREND E.W.: *Berechnung auflastinduzierter Horizontalverschiebungen, Geoidhöhen und Freiluft-Schwereanomalien für ein selbstgravitierendes, sphärisches Erdmodell und unterschiedliche Rheologien*. Geoforschungs-Zentrum Potsdam, Scientific Report STR99/24, Potsdam 1999.
- GRAFAREND E.W., ARDALAN A.A. (2001): *Time evolution on a world geodetic datum*. International Association of Geodesy Symposia 125 (2001) 114-121.
- HECK B.: *Erfassung neotektonischer Deformationen im Bereich des Oberrheingraben*; In: 2. SAPOS-Symposium, "SAPOS 2000 – Ihr Standpunkt", Berlin 1999, 106-110.
- HEIDBACH O., DREWES H.: *The velocity and strain field in the Mediterranean from deformation models*. Proceedings of the 10th WEGENER meeting, Boletín ROA No. 3/2000, San Fernando, Spanien, 2000.
- HEIDBACH O.: *Der Mittelmeerraum – Numerische Modellierung der Lithosphärendynamik im Vergleich mit Ergebnissen aus der Satellitengeodäsie*. Dt. Geod. Komm., Reihe C, Nr. 525, 2000.

- HOWIND J., SCHMITT G.: *Geodätische Überwachung einer Großhangbewegung in Ebnit/Vorarlberg*. Zeitschrift für Vermessungswesen 126 (2001), 1-5, 2001.
- KANIUTH K., DREWES H., STUBER K., TREMEL H., KAHLE H.-G., PETER Y., ZERBINI S., TONTI G., FAGARD H.: *Crustal deformations in the central Mediterranean derived from the WHAT A CAT GPS project*. In: Proceedings of the 13th Working Meeting on European VLBI for Geodesy and Astrometry, Viechtach, Febr. 12-13, edited by W. Schlüter and H. Hase, 192-197, 1999.
- KANIUTH K., DREWES H., STUBER K., TREMEL H.: *Bestimmung rezenter Krustendeformationen im zentralen Mittelmeer mit GPS*. Zeitschrift für Vermessungswesen, Jhrg. 126 (5), 256-262, 2001.
- KANIUTH K., MÜLLER H., SEEMÜLLER W.: *Displacement of the space geodetic observatory Arequipa due to recent earthquakes*. Zeitschrift f. Vermessungswesen (127), 238-243, 2002.
- KANIUTH K., HÄFELE P., SÁNCHEZ L. Z.: *Subsidence of the permanent GPS station Bogotá*. In: Drewes H., Dodson A., Fortes L. P., Sánchez L., Sandoval P. (Eds.): Vertical Reference Systems. IAG Symposia, Vol. 124, 56-59, Springer 2002.
- KHAZARADZE G., KLOTZ J., ANGERMANN D., MICHEL G. W., REIGBER C. (1999), *3d Modeling of Inter-seismic Strain Accumulation in the Central and Southern Andes Based on GPS Measurements* Suppl. EOS Trans. AGU, 80 (46), F270.
- KHAZARADZE G., KLOTZ J. (2001) *Interseismic Phase of Earthquake Deformation Cycle Dominates the Deformation Along the Central Andean Margin*, Geophysical Research Abstracts, 3, EGS 26th General Assembly, Nice.
- KHAZARADZE G., MICHEL G. W., KLOTZ J., HEINZE B., GRAEFE K. (2000): *Changes in Interplate and Intraplate Deformation Along the Central Andean Margin: A GPS and Neotectonic Study*, Geophysical Research Abstracts, 2, EGS 25th General Assembly, Nice.
- KHAZARADZE G., WANG K., KLOTZ J., HU Y., HE J. (2002), *Prolonged Post-seismic Deformation of the 1960 Great Chile Earthquake and Implications for Mantle Rheology*, Geophys. Res. Lett., Vol. 29, No. 22, 2050.
- KHAZARADZE G., KLOTZ J. (2003), *Short and Long-term Effects of Gps Measured Crustal Deformation Rates Along the South-central Andes*, J. Geophys. Res., in Press.
- KLOTZ J., ANGERMANN D., MICHEL G. W., PORTH R., REIGBER CH., REINKING J., VIRAMONTE J., PERDOMO R., RIOS V. H., BARRIENTOS S., BARRIGA R., CIFUENTES O. (1999), *GPS-derived Deformation of the Central Andes Including the 1995 Antofagasta Mw=8,0 Earthquake*, Pure and Appl. Geophysics 154, 709-730.
- KLOTZ J., ANGERMANN D., MICHEL REIGBER CH., CIFUENTES O., BARRIGA R., BARRIENTOS S., PERDOMO R., VIRAMONTE J., RIOS V. (1999), *Spatial and Temporal Variation of GPS-derived Deformation in the Central and Southern Andes*, Abstracts of XXII IUGG General Assembly, Birmingham, B.77.
- KLOTZ J., ANGERMANN D., MICHEL G. W., REIGBER CH., VIRAMONTE J., PERDOMO R., RIOS V. H. (1999), *Observaciones Geodésicas Para La Investigación De La Deformación Litosférica Andina*, Relatorio XIV Congreso Geológico Argentino, Salta, Tomo I, 4-5.
- KLOTZ J., ANGERMANN D., REIGBER CH., BARRIENTOS S., BARRIGA R., CIFUENTES O. (1999), *Deformación de la Cordillera de los Andes Sensada con GPS*, Resúmenes de V Convencion de Ingenieria en Geomensura y Ciencias Afines, Antofagasta, Chile, 28-31.
- KLOTZ J. (2000), *Geodätische Untersuchungen zur Deformation aktiver Kontinentalränder*, Habilitationsschrift, TU Berlin.
- KLOTZ J., KHAZARADZE G., REIGBER CH. (2000), *New Gps Results Along the Andean Subduction Zone*, Geophysical Research Abstracts, 2, Egs 25th General Assembly, Nice.
- KLOTZ J., KHAZARADZE G., ANGERMANN D., REIGBER CH., CIFUENTES O., BARRIGA R., BARRIENTOS S., PERDOMO R., VIRAMONTE J., RIOS V. (2000), *The Geodetic Observation of the Earthquake Deformation Cycle*, Proceedings of the IV. Congreso Internacional De Ciencias de la Tierra, Santiago de Chile, 78-82.
- KLOTZ J., KHAZARADZE G., CIFUENTES O., BARRIGA R., BARRIENTOS S., PERDOMO R., VIRAMONTE J., RIOS V. (2000), *the Present-day Kinematics of the Central and Southern Andes*, Suppl. EOS Trans. Agu, 81 (48), F1126-F1127.
- KLOTZ J., MICHEL G., KHAZARADZE G., HEINZE B. (2001), *GPS Based Deformation Measurements and Modeling*, Report of Sfb 267, Project D5, 361-394.
- KLOTZ J., KHAZARADZE G., ANGERMANN D., REIGBER C., PERDOMO R., CIFUENTES O. (2001), *Earthquake Cycle Dominates Contemporary Crustal Deformation in Central and Southern Andes*, Earth Planet. Sci. Lett. 193, 437-446.
- KLOTZ J., KHAZARADZE G., HEINZE B., MATURANA R., BATAILLE K., PERDOMO R. (2002), *Short-term and Long-term Deformation Field of the Andes*, Proceedings of VII Int. Congress on Earth Science, Santiago De Chile, Oct. 21 – 25.
- KRUMM F., GRAFAREND E. W. (2002): *Datum-free deformation analysis of ITRF networks*. Artificial Satellites 37 (2002) 75-84.
- LINDNER K., MAYER M., HECK B., KUTTERER H.: *Das geodätische Referenznetz Antarktis*. Proc. X. Int. Geodätische Woche, Obergurt/Österreich 1999. Univ. Innsbruck, Inst. für Geodäsie, Institutsmitteilungen Heft 18, 1999, 103-109.
- MARCHESINI C., SCHMITT G.: *Geodetic activities with respect to geokinematics in Friuli and the Eastern Alps*; Proceedings of the Second International Symposium Geodynamics of the Alps-Adria Area by Means of Terrestrial and Satellite Methods, Dubrovnik/Kroatien, 28.09.02.10.1998, 283-292.
- MAYER M., LINDNER K., KUTTERER H., HECK B.: *Determination of plate tectonic motion rates in the region of the Antarctic Peninsula*; IUGG 99, Birmingham/UK, abstracts, A. 51, 1999.
- MAYER M., LINDNER K., KUTTERER H., HECK B.: *Deformationsanalyse zur Aufdeckung von Punkt- und Blockbewegungen im Bereich der Antarktischen Halbinsel*. In: Dietrich R. (Ed.): Deutsche Beiträge zu GPS-Kampagnen des Scientific Committee on Antarctic Research (SCAR) 1995-1998. DGK B 310, München 2000, 127 – 144.
- MICHEL G. W., ANGERMANN D., KLOTZ J., REIGBER CH., XIA Y., WANG R. (1999), *Fault Motion and Strain Accumulation with GPS and InSAR: recent results from studies in Asia and S-America*, EGS newsletter, 103.
- MICHEL G. W., BECKER M., ANGERMANN D., REIGBER CH., REINHART E.: *Crustal motion in E and SE Asia from GPS measurements*. Earth, Planets and Space, 52 (2000) 713-720.
- MICHEL G. W., BECKER M., REIGBER CH., TIBI R., YU Y. Q., ZHU S. Y. (2001), *Regional GPS Data Confirms High Strain Accumulation Prior to the 2000 June 4 Mw = 7.8 earthquake*

- at Southeast Sumatra, Geophysical Journal International, Band 146, (3), 571-582.
- MICHEL G.W., YU QU.Y., ZHU S.Y., REIGBER CH., BECKER M., REINHART E., SIMONS W., AMBROSIUS B., VIGNY CH., CHAMOT-ROOKE N., LE PICHON X., MORGAN P., MATHEUSSEN S. (2001), *Crustal Motion and Block Behaviour in Sasia from GPS Measurements*, Earth and Planetary Science Letters 187, 239-244.
- MINYU JIA, XING CANFEI, LI HUI, SUN SHAOAN, TORGE W., TIMMEN L., SCHNÜLL M., RÖDER R.: Gravity changes with time in Yunnan and Beijing observed by absolute gravimetry. In: Earthquake Research in China, Vol. 15, No. 1, 54-64, 1999.
- REBSCHER D., WESTERHAUS M., KÖRNER A., WELLE W., SUBANDRIYO, BRODSCHOLL A., KÜMPEL H.-J., ZSCHAU J.: *Indonesian-German Multiparameter Stations at Merapi Volcano*. In: Buttkeus B., Greinwald S., Oswald J. (Ed.): *Decade Volcanoes Under Investigation. 2. Merapi-Caleras Workshop*, Deutsche Geophysikalische Gesellschaft, Sonderband IV/2000, 93-102.
- REBSCHER D., WESTERHAUS M., WELLE W. NANDAKA I. G. M.: *Monitoring Ground Deformation at the Decade Vlocano Gunung Merapi, Indonesia*. Phys. Chem. Earth, vol. 25, 2000, 755-757, 2000.
- REIGBER CH., MICHEL G., GALAS R., ANGERMANN D., KLOTZ J., CHEN J.Y., PAPSHEV A., ARSLANOV R., TZURKOV V.E., ISHANOV M.C. (2001), *New Space Geodetic Constraints on the Distribution of Deformation in Central Asia*, Earth Planet. Sci. Lett. 191, 157-165.
- RUS T., BECKER M. (2001): *Data Evaluation of the CEGRN-99 GPS Campaign at the BKG Processing Centre*. EGS XXVI Gen. Ass. Nice, France, March 2001, Geodetic and Geodynamic Programmes of the CEI Symp. G9, Reports on Geodesy, No 2 (57), pp. 129-144, Warszawa.
- SACHER M., IHDE J., SCHOCH H., GIRRLAT D., MOLENDIJK R., SCHMIDT K.: *Preliminary results of test computations as a first step to a kinematic height network*; In: Veröff. Bayer. Komm. Int. Erdmess., Bayer. Akad. d. Wiss., Astron.-geod. Arb., München, 2000, H. 61, S. 116-125.
- SCHEUBER E., CHARRIER R., GONZALEZ G., KLOTZ J., REUTHER C.-D., REUTTER K.J. (2000), *Crustal Evolution of the Southern Central Andes (20°S-26°S) Since the Jurassic*, Zeitschr. F. Angewandte Geologie, Sh1, 323 – 329.
- SCHMITT G., LEMP D.: *Long-term monitoring of recent crustal movements in the Eastern Alps (GPS-project "Alpen-traverse")*; Reports on Geodesy, Warsaw University of Technology, 2 (57), 2001, 21 – 28.
- SCHÖN S., KUTTERER H.: *Optimal design of geodetic monitoring networks by means of interval mathematics*. C. Whitacker (Ed.): Proceedings of the 10th FIG International Symposium on Deformation Measurements. March 19-22, 2001, Orange/USA, 362-371, 2001.
- SEEMÜLLER W., KANIUTH K., DREWES H.: Velocity estimates of IGS RNAAC SIRGAS stations. In: Drewes H., Dodson A., Fortes L.P., Sánchez L., Sandoval P. (Eds.): *Vertical Reference Systems*. IAG Symposia, Vol. 124, 7-10, Springer 2002.
- TESMER V.: *VLBI Solution DGF101R01 based on Least-Squares Estimation Using OCCAM 5.0 and DOGS-CS*. In: Vandenberg N., Bayer K. (Eds.): *IVS 2002 General Meeting Proceedings*, NASA/CP-2002-210002, 295-299, 2002.
- TORGE W., SCHNÜLL M., TIMMEN L., JIA MINYU, XING CANFEI, LI HUI: Absolute and relative gravimetry 1990/1992/1995 in the Western Yunnan Earthquake Prediction Experimental Area. Deutsche Geodätische Kommission, Reihe B, Nr. 307, München, 1999.
- VÖLKSEN C.: *Die Nutzung von GPS für die Deformationsanalyse in regionalen Netzen am Beispiel Islands*; In: Wissenschaftliche Arbeiten Fachrichtung Vermessungswesen, Univ. Hannover, 2000, Nr. 237, 151 S.
- WILSON P., MICHEL G.W., RAIS J. (2000), *Das Projekt GEO-DYSSEA*, Zeitschrift für Vermessungswesen, Heft 3, 70-74.
- WESTERHAUS M., WYSS M., RÜCHAN Y., ZSCHAU J.: *Correlation variations of b values and crustal deformations during the 19902 may have pinpointed the rupture initiation of the Mw=7,4 Izmit earthquake of 1999 August 17*. Geophys. J. Int., 148 (2002), 139 – 152, 2002.
- WESTERHAUS M., WELLE W.: *Environmental effects on tilt measurements at Merapi volcano*. Bulletin d'Information des Marées Terrestres, 137 (2002), 10971- 19026, 2002.
- WESTERHAUS M., ZSCHAU J.: *No clear evidence for temporal variations of tidal tilt prior to the 1999 Izmit and Düzce earthquakes in NW-Anatolia*. J. Geod. Soc. Japan, Vol. 47 (2001), 448-455, 2001.

Tidal and non-tidal gravity field variations

B. RICHTER¹

Instrumentation, tidal recording and tidal models

Superconducting gravimetry:

G. JENTZSCH, C. KRONER, University Jena:

Since Eastern 1999 the dual-sphere superconducting gravimeter CD 034 is operating in our Geodynamical Observatory Moxa close to Jena. Thus, Moxa is one station within the Global Geodynamics Project. Both sensors show only minor differences and the record is very stable. The polar motion signal is clearly observed and after all corrections (including ocean loading) the observed phase shifts of the main tidal waves correspond to the theoretical expected values. Our research concentrates on environmental effects on gravity and the study of geodynamical signals in the gravity record.

J. NEUMAIER et al., GFZ :

In February 2000 the reconstructed Dual Sphere Superconducting Gravimeter (SG) with two gravity sensors has been installed at the newly constructed South African Geodynamic Observatory Sutherland (SAGOS). Additionally meteorological sensors and a ground water table sensor are installed for estimation of gravity changes induced by the atmosphere and hydrosphere. The quality of the site is discussed according to the requirements for a SG site. The difference of the tilt minima for both sensors is adjusted to about 4.5 nm/s^2 . For both gravity sensors the calibration factors have been determined by comparison with a well calibrated LaCoste & Romberg Gravimeter which records to the SG in parallel. With a recently developed low frequency sine and square wave generator based on a PC a step response experiment has been carried out to determine the transfer function and to calculate the instrumental time lag. The station is remote controlled by a "Multi Media Monitoring Controlling and Information System" (M³CIS) which operates in real time via Internet. The preliminary short period tidal parameters have been determined for both sensors which are in good agreement. An amplitude spectrum presents the gravity residuals. The single atmospheric pressure admittance is determined for both sensors.

G. HARNISCH et al., BKG:

In the last years the superconducting gravimeters of the Bundesamt für Kartographie und Geodäsie (BKG) have been calibrated several times by comparison with absolute gravity measurements. Averaging over all measuring campaigns, stable results with errors in the order of $1 \text{ nm s}^{-2}/\text{V}$ are reached. Three of the instruments were also calibrated by

the platform method. The internal accuracy of this method is higher by about one order of magnitude. However, there are discrepancies between the results of the two different calibration methods, the origin of which is still not clear.

G. HARNISCH et al., BKG:

Gravity data recorded by superconducting gravimeters at different stations around the world are used to estimate the gravity effect of polar motion. All data were uniformly reprocessed. After drift elimination the annual and the Chandler wobble were separated by fitting a combination of two sinusoidal functions with periods of 365.25 and 432 days to the residual gravity variations. The majority of the 6-factors of both constituents vary between 1.0 and 1.5 with a tendency to 1.2. Because of diverse uncertainties and disturbances, which could not be completely eliminated, a detailed evaluation of the 6-factors and of the phase values K is not possible as yet.

Other gravimeters:

H.-J. DITTFELD, GFZ:

On the 10th Earth Tide Symposium in Madrid 1985 an investigation was referred concerning – among other tasks – tidal gravity results of two similar stations in Berlin and in Potsdam/Germany. There have been compared the results of contemporary time series of two different tidal gravimeters (LaCoste&Romberg ET18 and ASKANIA GS15 No, 222). Deviations of the amplitude factors at both stations were observed with a mean value in the order of 0.7 percent.

Nowadays it became possible to perform such measurements with a more up-to-date equipment and to evaluate it with improved methods. So was installed a LaCoste&Romberg (Type G) gravimeter between 1997 and 1999 in turns at both the stations and the time series were analysed using the ETERNA 3.3 analysis program. Deviations of the tidal amplitudes are nearly of the same amount as in the 1978/1980 measurements but with an opposite sign. Therefore possible reasons are discussed with regard to the quality of the error estimations. Furthermore a lower noise level was observed in both periods at Insulaner station in the inner city of Berlin.

Tiltmeter, Seismometer:

G. JENTZSCH, University Jena:

Since 1997 the seismological station, Moxa, has been reconstructed and extended to become a geodynamic broadband observatory. Seismological observations are carried out with a seismometer STS-2 (3-component) now suppl-

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mented with a three component STS-1, a long period seismometer, which usually operates at up to 360 seconds but is also sensitive to tidal signal. The original east-west and north-south quartz strainmeters were reconstructed and equipped with new inductive sensor systems. A laser strainmeter, orientated from north-west to south-east, has also been newly installed. The beam runs through a horizontal borehole. All three components show clearly the expected tidal strain variations. Cavity effects seem to be small. In front of the observatory buildings three boreholes, two 50 meter and one 100 meter, were drilled and first test recordings with the ASKANIA borehole tiltmeter were carried out. As an optical estimation of the pendulum azimuth was not possible, a new method was developed by use of seismological observations from well-known locations. Signals and noise recorded by the different sensor systems were investigated in particular not only for seismological frequencies, but also for very long period.

Tidal models

J. MÜLLER, IfE, University Hannover:

Müller et al. (2002) give an overview which tidal models are used worldwide in the various computer programs for the analysis of Lunar Laser Ranging (LLR) data and which tidal parameters are determined by LLR, e.g. the lunar tidal acceleration or Love numbers of the Moon. Müller and Tesmer (2002) continue these investigations and discuss also how well terrestrial Love numbers (h_2 , l_2) or amplitudes of typical diurnal and semi-diurnal periods can be derived from LLR data.

Solid earth, ocean and loading tides

G. JENTZSCH, University Jena:

Ocean tidal loading is a cause for crustal deformation, especially close to the coast. In Greenland, fiducial sites are located just near the coast and are affected by deformation which cannot be corrected sufficiently by current ocean tidal models. Therefore, using local gravity tidal measurements over one year at each of the four stations, the ocean tidal models could be checked and the differences quantified. They amount to up to some centimeters over the whole spectrum which is in the order of the resolution of air borne and satellite based monitoring of the changes of the Greenland ice cover.

Gravity field variations of tectonic origin

G. JENTZSCH, University Jena:

Tilt, especially tidal tilt measurements monitor the variations of the direction of the gravity vector. The signals are extremely affected by local disturbances, e.g. local loads. In spite of this it could be shown that in the case of suitable coupling of the tiltmeter to the ground and deep installation the data is representative for deformation and gravity changes (horizontal gradient). Thus, also tectonic signals can be separated.

Environmental parameters and geophysical interpretation

G. JENTZSCH et al., University Jena:

In addition to effects due to variations in barometric pressure changes in hydrological quantities can be sources for significant effects in gravity. At the Geodynamic Observatory Moxa (Germany) the influence of fluctuations in groundwater table and soil moisture on gravity data recorded with the dual sphere superconducting gravimeter CD 034 is studied. Up to now effects caused by variations in soil moisture/fissure water and water level could be detected. Due to the location of the observatory in a small valley and the fact that sections of it are built into a hill a major part of the hydrological changes occurs above the gravimeter level. Therefore, an increase in the amount of water in the observatory area generally leads to a decrease in gravity and vice versa. Since the hydrological effects are in the range of some to several 10 nm/s^2 they must be removed from the gravity data. Initial attempts to develop a correction method are made.

Crustal deformation monitoring combined with seismic observations can be used in areas of high earthquake hazard in a joint interpretation for progress in earthquake research. Therefore, the 'Earthquake Research Institute' of Tokyo University runs the Nokogiriyama Observatory at the bay of Tokyo complementary to the seismological array. In April 1997 an Askania tiltmeter was deployed in a 10 m deep borehole in the observation gallery supplementary to the already installed water tube tiltmeters. It operated with only a small drift until June 1999. Recordings of the Askania and the water tube tiltmeters are compared with each other regarding signal/noise ratios, tidal residuals, ocean loading and meteorological effects to evaluate advantages and limitations of both instruments concerning future use in earthquake areas. First results of this comparison indicate generally good correspondence between the signals of the two instruments. Similarities and differences in the long-term drift, the tidal parameters and hydrologically and air pressure induced signals are discussed.

B. RICHTER et al., BKG:

In the framework of the European Union SELF II project, a study was developed in order to assess the accuracy with which vertical crustal movements could be determined by means of continuous GPS and gravity observations in a relatively short time-span of a few years. The reliable knowledge of vertical rates at tide gauge stations is necessary to properly interpret sea level variations. For height determinations, continuous GPS and gravity measurements started in mid-1996 at Medicina, in the southern Po Plain. The time variability of gravity and GPS heights in relation to variations of several environmental parameters was investigated.

A marked seasonal signal has been identified in both data series. It has been interpreted as the sum of different loading and Newtonian attraction effects modelled on the basis of the relevant environmental data series. At Medicina, the comparison between height and gravity series has shown that the seasonal variations are quite comparable both in amplitude and phase. A seasonal oscillation in the order of 18 mm (peak-to-peak amplitude) is present in the height data.

This crustal deformation has been modelled by including variations in the atmospheric, oceanic and hydrologic mass. The vertical positions can also be affected significantly by soil consolidation. Geotechnical parameters derived by in-situ tests and laboratory analyses of the clayey soil collected at Medicina allowed the estimate of the soil settlement relevant to the seasonal oscillation of the surficial water table. Thermal expansion of the geodetic monument has to be taken into account in the case of high-precision vertical positioning. Models both for the soil consolidation and the thermal expansion effects have been derived. The continuous gravity observations collected at Medicina by means of a superconducting gravimeter also exhibit a marked seasonal oscillation, which has been interpreted as the sum of loading and Newtonian attraction effects, as well as of the contribution due to soil consolidation. Especially the study concerning the soil consolidation effect has allowed a better insight on the seasonal vertical movements occurring at the Medicina station by providing quantitative information on soil behaviour due to change of effective pressures. The results can be applied to those stations characterized by similar fine-grained soils and surficial hydrogeology.

H.-J. DITTFELD, GFZ:

While the significance of air pressure coefficients in tidal analysis results is unquestionable, and their application clearly improves the results, the correlation with other environmental parameters is often weak and improvements are rather small if they are introduced. In spite of the progress in modelling in recent years, there seems to be a limit to the accuracy that can be achieved, and one has rather to look for possibilities of avoiding some environmental influences from the beginning.

Some reasons for the disappointing success of this correlation are here discussed for a 6-year recording of a superconducting gravimeter operating in Potsdam. We are particularly concerned with ground water level, room temperature, and rainfall. Even though the residual noise is more or less decreased, the results are practically independent of the influence of the additional parameters. It is shown that the correlation is not persistent enough through the data to achieve the expected improvement, or perhaps on the other hand the actual influences are partly screened. For example, the effect of rainfall is difficult to estimate if the water flows superficially away from the station and the soil moisture does not correspond to the precipitation at the point of the rain gauge.

M. WESTERHAUS et al., Observatory Schiltach:

During the IDNDR decade geodynamic monitoring stations have been installed in many tectonically active areas. The improvement of sensor- and data acquisition techniques considerably broadened the observation of strain induced (tidal) signals, including an increasing number of 'non-classical' quantities like physico-chemical parameters of ground water or electrical resistivity. As a continuous and well known source of deformation acting on the earth at any place and any time, earth tides provide a unique possibility to validate the coupling of the sensors to the ground, to carry

out in situ calibrations and to check the temporal stability of the response characteristics. The response to an imposed tidal strain may provide insight into the physics and the linearity/non-linearity of the strain coupling mechanisms which is important especially for 'natural' strain sensors like wells and thermal/mineral springs. If the recording system provides calibration facilities, the local tidal response functions may be investigated with respect to changes of mechanical properties of the crust during the preparation of earthquakes and volcanic eruptions.

Since 1985, Earth tidal signals in borehole tilt- and well level data are investigated with respect to changes in the state of deformation along a 60 km long segment of the North-Anatolian Fault, about 200 km east of Istanbul, Turkey. Modifications of up to 100% in amplitude and 80° in phase (with respect to the response on a laterally homogeneous earth) of the static tidal tilt response functions are essentially explained by the presence of the fault zone. The strong influence of the shear zone varies over time by not more than 4% in amplitude and 3° in phase. Despite the short distance of the 6 stations to the epicenters of the 1999 catastrophic earthquakes of Izmit and Düzce (60 km - 110 km and 17 km - 44 km, respectively) no significant pre-, co- or postseismic variations of the local tidal tilt response functions were detected.

Literature

- CROSSLEY, D., J. HINDERER, G. CASULA, O. FRANCIS, H.-T. HSU, Y. IMANISHI, G. JENTZSCH, J. KÄÄRIÄINEN, J. MERRIAM, B. MEURERS, J. NEUMEYER, B. RICHTER, K. SHIBUYA, T. SATO, T. VAN DAM, 1999. *Network of superconducting gravimeters benefits a number of disciplines*. EOS Transactions, vol. 80, No. 11.
- DITTFELD, H.-J., 2000. Final results of the SG-registration in Potsdam. Cah. Centre Europ. Geodyn. Seism., Luxembourg 2000, Vol. 17. – p. 11-24.
- DITTFELD, H.-J., 2001. *Tidal results of Neighbouring Stations* (Part III of an old investigation). Proc. 14th International Symposium on Earth Tides, Special Issue of the Journal of the Geodetic Soc. of Japan, 47/1, 148-154.
- DITTFELD, H.-J., 2001. *On the validity of environmental parameters in gravimetric tidal analyses*. Proc. 14th International Symposium on Earth Tides, Special Issue of the Journal of the Geodetic Soc. of Japan, 47/1, 287-293.
- FALK, R., M. HARNISCH, G. HARNISCH, I. NOWAK, B. RICHTER, P. WOLF, 2001. *Calibration of the Superconducting Gravimeters SG 103, C023, CD029 and CD030*. Proc. 14th International Symposium on Earth Tides, Special Issue of the Journal of the Geodetic Soc. of Japan, 47/1, 22-27.
- HARNISCH, M., HARNISCH, G., NOWAK, I., RICHTER, B., WOLF, P., 2000. *The dual sphere superconducting gravimeter CD029 at Frankfurt a. M. and Wettzell: first results and calibration*. Cah. Centre Europ. Geodyn. Seism., Luxembourg 2000, Vol. 17. – p. 39-56.
- HARNISCH, M., HARNISCH, G., JURCUYK, H., WILMES, H., 2000. *889 days of registrations with the Superconducting Gravimeter SG103 at Wettzell (Germany)*. Cah. Centre Europ. Geodyn. Seism. Luxembourg 2000, Vol. 17. – p. 25-37.
- HARNISCH, M., HARNISCH, G., 2001. *Study of long-term gravity variations, based on data of the GGP co-operation*. Proc.

- 14th International Symposium on Earth Tides, Special Issue of the Journal of the Geodetic Soc. of Japan, 47/1, 322-327.
- ISHII, H., G. JENTZSCH, S. GRAUPNER, S. NAKAO, M. RAMATSCHI, A. WEISE, 2001. *Observatory Nokogiriyama / Japan: comparison of different tiltmeters*. Proc. 14th International Symposium on Earth Tides, Special Issue of the Journal of the Geodetic Soc. of Japan, 47/1, 155-160.
- JAHR, T., G. JENTZSCH, C. KRONER, 2001. *The Geodynamic Observatory Moxa / Germany: Instrumentation and purposes*. Proc. 14th International Symposium on Earth Tides, Special Issue of the Journal of the Geodetic Soc. of Japan, 47/1, 34-39.
- JENTZSCH, G., C. KRONER, 1999. *Environmental effects on the gravity vector – a short overview*. Bulletin d'Information Marees Terrestres, 131, 10105-10112.
- KRONER, C., G. JENTZSCH, 1999. Comparison of different barometric pressure reductions for gravity data and resulting consequences. *Phys. Earth and Plan. Int.*, 115, 205 – 218.
- KRONER, C., JAHR, T., JENTZSCH, G., 2001. *One year of recording with the dualsphere Superconducting Gravimeter CD034 at the Geodynamic Observatory Moxa / Germany*. Proc. 14th International Symposium on Earth Tides, Special Issue of the Journal of the Geodetic Soc. of Japan, 47/1, 398-403.
- KRONER, C., 2001. *Hydrological effects on gravity at the geodynamic observatory Moxa*. Proc. 14th International Symposium on Earth Tides, Special Issue of the Journal of the Geodetic Soc. of Japan, 47/1, 353-358.
- KRONER, C., JAHR, TH., JENTZSCH, G., 2002. *Comparison of results obtained with a dual sensor superconducting gravimeter*. Bull. d'Inf. Marees Terr., 135, 10617-10620.
- KRONER, C., 2002. *Zeitliche Variationen des Erdschwerefeldes und ihre Beobachtung mit einem supraleitenden Gravimeter im Geodynamischen Observatorium Moxa*. Habilitationsschrift, Jenaer Geowiss. Schriften, Heft 2
- KRONER, C., JAHR, TH., JENTZSCH, G., 200?. *Geodynamic Observatory Moxa: A key station for worldwide superconducting gravimetry*, *Geophys. J. Int.*, submitted
- NEUMEYER, J., BARTHELMES, F., DITTFELD, H.-J., 2001. *Ergebnisse aus einer sechsjährigen Registrierung mit dem Supraleitgravimeter (SG) am GFZ Potsdam*. *Z. Vermess. wes.*, Stuttgart 126 (2001) 1. – p. 15-22.
- NEUMEYER, J., E. BRINTON, P. FOURIE, H.-J. DITTFELD, H. PFLUG, B. RITSCHEL, 2001. *Installation and first data of the dual sphere superconducting gravimeter at the South Africa geodynamic observatory Sutherland*. Proc. 14th International Symposium on Earth Tides, Special Issue of the Journal of the Geodetic Soc. of Japan, 47/1, 316-321.
- PETERS, T., 2001. *Zeitliche Variationen des Gravitationsfeldes der Erde*, IAPG/FESG-Schriftenreihe, No. 12, 2001.
- ROMAGNOLIA, C., S. ZERBINI, L. LAGOB, B. RICHTER, D. SIMONE F. DONZENICHINIB, C. ELMIA, M. GHIROTTIA, 2003. *Influence of soil consolidation and thermal expansion effects on height and gravity variations*. *J. of Geodynamics*, 35, 521-539.
- SUN, H.-P., H.-T. HSU, G. JENTZSCH, AND J.-Q. XU, 2002. *Tidal gravity observations obtained with a superconducting gravimeter at Wuhan / China and its application to geodynamics*. *J. Geodynamics*, 33, 187 – 198.
- WESTERHAUS, M., W. ZÜRN, 2001. *On the use of Earth tides in Geodynamics Research*. Proc. 14th International Symposium on Earth Tides, Special Issue of the Journal of the Geodetic Soc. of Japan, 47/1, 398-403.
- WESTERHAUS, M., J. ZSCHAU, 2001. *No clear evidence for temporal variations of tidal tilt prior to the 1999 Izmit and Düzce Earthquake in NW-Anatolia*. Proc. 14th International Symposium on Earth Tides, Special Issue of the Journal of the Geodetic Soc. of Japan, 47/1, 448-455.
- ZERBINI, S., M. NEGUSINI, C. ROMAGNOL, F. DOMENICHINI, B. RICHTER, D. SIMON, 2002. *Multi-parameter continuous observations to detect ground deformation and to study environmental variability impacts*. *Global and Planetary Change*, 34, 37-58.

Sea Level and Ice Sheets

R. DIETRICH¹

1. Monitoring of Long-Term Sea-Level Changes and GPS Tide Gauge Benchmark Monitoring

The global sea level is a key quantity in the Earth's climate system. Tide gauge data provide long-term information on relative sea-level changes, whereas a GPS monitoring of tide gauge benchmarks allows the separation of vertical crustal movements and sea-level change in the global geocentric coordinate frame.

In the southern Baltic Sea, long-term sea-level data were reduced in order to provide homogeneous time series, and the regional pattern of sea-level rise was determined (LIEBSCH et al. 2000; DIETRICH and LIEBSCH 2000). The analysis of sea-level changes in the Mediterranean showed regional differences in the sea-level rate, but since the 1990's an increase of this rate can be observed at all of the analyzed PSMSL stations (FENOGLIO-MARC and MARTINEZ-GARCIA 2001; FENOGLIO-MARC 2002a; FENOGLIO-MARC 2002b).

The GPS monitoring of tide gauge benchmarks is a key issue of the IAG Special Commission 8 and of the IGS TIGA pilot project. The SEAL project intends an integrated approach of different research centres and contributes substantially to this important task (REIGBER et al. 2001). Within the scope of the EVAMARIA project, several Atlantic tide gauge benchmarks are monitored by GPS (BOSCH et al. 2002; HÄFELE et al. 2002). Antarctic tide gauges were also linked to the ITRF by GPS observations (SCHÖNE et al. 1999).

2. Sea-Surface Changes from Altimetry, and Its Consequences for Oceanography, Gravity Field Determination, and Earth Rotation

For the study of the sea surface and its variability, satellite altimetry is a powerful tool which provides data with almost global coverage in high temporal resolution. The global sea surface from altimetry has been used to estimate ocean mass redistribution (GRUBER et al. 2000), and to discuss its impact on the global height system definition (BOSCH 2002b). In order to investigate the sea-level variability and its causes, regional studies were carried out in the North Atlantic Ocean (ESSELBORN et al. 2001; Esselborn and Eden 2001), in the Mediterranean (FENOGLIO-MARC et al. 2000; FENOGLIO-MARC and GROTEN 2003), and in the Caribbean Sea (BOSCH et al. 2002).

The role of sea-surface changes in gravity field determination is discussed (REIGBER et al. 1999), and effects of the sea level on earth rotation and length-of-day are investigated

by several authors (HÖPFNER 2001b; JOCHMANN 2002; WÜNSCH 2002b).

3. Altimeter Calibration/Validation and Inter-comparison of Techniques

For consistent sea-level observations, unbiased altimeter data are required (see e.g. BOSCH 2002a). This involves the determination of relative mission biases as well as absolute offsets and drift rates for single altimeter missions.

Within the calibration/validation activities for recent satellite altimeter missions, GPS buoys in the North Sea (SCHÖNE et al. 2000) were operated. The regional unification of different altimeter missions was performed using crossover differences in the Mediterranean (FENOGLIO-MARC 2001b; FENOGLIO-MARC and GROTEN 2002b). For the Baltic Sea, absolute altimeter bias and drift rates for several missions were determined by comparison with tide gauges (LIEBSCH et al. 2002).

Another source for information about sea-surface heights are oceanographic models. The intercomparison of tide gauge, altimetry and oceanographic modelling in the Baltic Sea showed a consistency of the different height observations and information of a few centimetres (NOVOTNY et al. 2002).

4. Ice Sheet Topography, Dynamics, and Mass Balance

Precise surface elevations of the Antarctic ice sheet were determined from ERS radar altimetry on continental-wide scale (IHDE et al. 2002). In Antarctica, regional investigations to study the ice flow of outlet glaciers by SAR interferometry were focussed on Mertz Glacier (PÖTZSCH et al. 2000) and the region of Schirmacher Oasis (DIETRICH et al. 1999). Further, the mass balance of polar ice sheets was investigated based on model computations (HUYBRECHTS 2001).

5. Ice – Ocean – Solid Earth Interactions

The dynamics of the ice sheets due to climatic and other influences causes complex interactions with the ocean and with the solid earth. The impact of ice mass changes on sea level for glacial cycles was investigated (HUYBRECHTS 2002). Further, the impact of ice mass changes on gravity and geoid was discussed (LE MEUR and HUYBRECHTS 2001).

The dynamics of ice shelves, especially of the grounding zone due to tidal motions was studied in detail (RIEDEL et al. 1999; RIEDEL 2002a; RIEDEL 2002b). The migration of

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the grounding line due to tides can amount to several kilometres as was observed by SAR interferometry (METZIG et al. 2000). Tidal signals at the subglacial Lake Vostok in Antarctica were discovered (DIETRICH et al. 2001). Tidal loading effects at the Antarctic Peninsula were analyzed using GPS data (DACH and DIETRICH 2001).

The solid Earth response to ice mass changes based on a viscoelastic Earth model was investigated for Alaska (BÖLLING et al. 2001), and its consequences for tide gauge observations at Svalbard (HAGEDOORN and WOLF 2003).

Literature

- ACUÑA, G., W. BOSCH, B. MEISEL (2002). *Correlation between multi-mission altimeter time series and tide gauge registrations in the Caribbean sea*. In H. Drewes, A. Dodson, L. Fortes, L. Sánchez, and P. Sandoval (Eds.), Vertical Reference Systems, Volume 124 of Springer Series of IAG Symposia, pp. 231-237.
- BÖLLING, K., J. HAGEDOORN, D. WOLF, E. GRAFAREND (2001). *Berechnung eislastinduzierter Vertikalbewegungen und Geoidänderungen in Südostalaska mit Hilfe viskoelastischer Erdmodelle*. Sci.Techn.Rep. GFZ Potsdam, STR01/08, 46pp.
- BOSCH, W. (2000). *CSTG Subcommission on Multi-Mission Satellite-Altitude (ScomMSA)*. IAG CSTG Bulletin No. 16, 59-61, Munich.
- BOSCH, W. (2001). *EOF Analysen der Meeresspiegelschwankungen im Pazifik*. Zeitschrift für Vermessungswesen 126(2), 74-81.
- BOSCH, W. (2002a). *Multi mission satellite altimetry continuing*. IAG CSTG Bulletin No. 17, 60-63, Munich.
- BOSCH, W. (2002b). *The sea surface topography and its impact to global height system definition*. In H. Drewes, A. Dodson, L. Fortes, L. Sánchez, and P. Sandoval (Eds.), Vertical Reference Systems, Volume 124 of Springer Series of IAG Symposia, pp. 225-230.
- BOSCH, W., G. ACUÑA, R. KANIUTH (2002). *Caribbean sea level variability from TOPEX/Poseidon altimetry*. In H. Drewes, A. Dodson, L. Fortes, L. Sánchez, P. Sandoval (Eds.), Vertical Reference Systems, Volume 124 of Springer Series of IAG Symposia, pp. 249-254.
- BOSCH, W., H. DREWES, P. HÄFELE, K. KANIUTH, R. KANIUTH, M. KUHN, K. STUBER, H. TREMEL (2002). *The EVAMARIA project: Identification and verification of sea level anomalies in the North Atlantic*. In H. Drewes, A. Dodson, L. Fortes, L. Sánchez, P. Sandoval (Eds.), Vertical Reference Systems, Volume 124 of Springer Series of IAG Symposia, pp. 238-243.
- BOSCH, W., J. KLOKOCNIK, C. WAGNER, J. KOSTELECKY (2000). *Geosat and ERS-1 datum offsets relative to Topex/Poseidon estimated simultaneously with geopotential corrections from multi-satellite crossover altimetry*. In R. Rummel, H. Drewes, W. Bosch, H. Hornik (Eds.), IAG Section II Symposium: Towards an Integrated Global Geodetic Observing System (IGGOS), Volume 120 of Springer Series of IAG Symposia, pp. 96-98.
- BOSCH, W., M. KUHN, M. BAUMGARTNER, R. KANIUTH (2001). *Überwachung des Meeresspiegels durch Satellitenaltimetrie – Ergebnisse und Folgerungen für die Geodäsie*. Zeitschrift für Vermessungswesen 126(5), 262-269.
- BRAUN, A. (1999). *Calibration of ERS altimetry data through tide gauge data in the western Spitsbergen shelf*. Technical report, Scientific field report LSF Ny-Alesund, grant NMA-99/2-1.
- BRAUN, A., S. EICKSCHEN, A. HELM, M. RENTSCH, T. SCHÖNE (2000). *The ENVISAT RA-2 Value-Added Ocean/Ice Processor at GFZ Potsdam*. ESA – ERS/ENVISAT Symposium, Gothenburg, Sweden, Oct 2000, Abstract volume. Braun, A., A. Helm, C. Reigber, M. Rentsch, T. Schöne (2000). *Altimetrie und Meeresspiegel*. Technical report, Zweijahresbericht 1998/199, GeoForschungsZentrum Potsdam (GFZ), p. 13-27.
- CHEN, X., M. FORBERG, H.-W. SCHENKE, M. POHL, T. SCHÖNE, C. LE PROVOST (2000). *Auswertung von Daten der SCAR-GPS-Kampagnen und Permanentstationen in der Antarktis und Umgebung*. In R. Dietrich (Ed.), Deutsche Beiträge zu GPS-Kampagnen des Scientific Committee on Antarctic Research (SCAR) 1995-1998, pp. 45-58. DGK, Reihe B, Heft Nr. 310, München.
- CHURCH, J., J. GREGORY, P. HUYBRECHTS, M. KUHN, M. C. LAMBECK, D. Q. NHUAN, P. WOODWORTH (2001). *Changes in sea level*. In J. Houghton, Y. Ding, D. Griggs, M. Noguer, P. van der Linden, X. Dai, K. Maskell, C. Johnson (Eds.), *Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 639-694. Cambridge University Press (Cambridge, New York).
- DACH, R. (2000). *Auswirkungen von Auflastdeformationen durch Ozeangezeiten auf die GPS-Auswertung*. In R. Dietrich (Ed.), Deutsche Beiträge zu GPS-Kampagnen des Scientific Committee on Antarctic Research (SCAR) 1995-1998, pp. 211-218. DGK, Reihe B, Heft Nr. 310, München.
- DACH, R. R. DIETRICH (2000). *Influence of the ocean loading effect on GPS derived precipitable water vapor*. Geophysical Research Letters 27(18), 2953-2958.
- DACH, R. R. DIETRICH (2001). *The ocean loading effect on the GPS analysis: A case study in the Antarctic Peninsula Region*. Marine Geodesy 24(1), 13-25.
- DACH, R., R. DIETRICH, W. KORTH, J. PERLT (2000). *Auswertestrategie und Ergebnisse der Auswertegruppe der TU Dresden für die SCAR GPS Kampagnen*. In R. Dietrich (Ed.), Deutsche Beiträge zu GPS-Kampagnen des Scientific Committee on Antarctic Research (SCAR) 1995-1998, pp. 31-44. DGK, Reihe B, Heft Nr. 310, München.
- DEPENTHAL, C., M. MAYER, H. KUTTERER, K. LINDNER, B. HECK (2000). *Einfluss der Atmosphäre auf GPS-Beobachtungen im Bereich der Antarktis*. In R. Dietrich (Ed.), Deutsche Beiträge zu GPS-Kampagnen des Scientific Committee on Antarctic Research (SCAR) 1995-1998, pp. 195-200. DGK, Reihe B, Heft Nr. 310, München.
- DIETRICH, R., R. DACH, G. ENGELHARDT, J. IHDE, W. KORTH, H. KUTTERER, K. LINDNER, M. MAYER, F. MENGE, H. MILLER, C. MÜLLER, W. NIEMEIER, J. PERLT, M. POHL, H. SALBACH, H.-W. SCHENKE, T. SCHÖNE, G. SEEBER, A. VEIT, C. VÖLKSEN (2000). *Ergebnisse der SCAR GPS Kampagnen – ITRF-Koordinaten und Geschwindigkeiten*. In R. Dietrich (Ed.), Deutsche Beiträge zu GPS-Kampagnen des Scientific Committee on Antarctic Research (SCAR) 1995-1998, pp. 10-20. DGK, Reihe B, Heft Nr. 310, München.
- DIETRICH, R., R. DACH, G. ENGELHARDT, J. IHDE, W. KORTH, H.-J. KUTTERER, K. LINDNER, M. MAYER, F. MENGE, H. MILLER, C. MÜLLER, W. NIEMEIER, J. PERLT, M. POHL, H. SALBACH, H.-W. SCHENKE, T. SCHÖNE, G. SEEBER, A. VEIT, C. VÖLKSEN (2001). *ITRF coordinates and plate velocities*

- from repeated GPS campaigns in Antarctica – an analysis based on different individual solutions. *Journal of Geodesy* 74(11/12), 756-766.
- DIETRICH, R., R. DACH, J. PERLT, H.-W. SCHENKE, T. SCHÖNE, M. POHL, G. SOLTAU, G. ENGELHARDT, H. MIKOLAISKI, G. SEEBER, F. MENGE, W. NIEMEIER, H. SALBACH, K. LINDNER, H.-J. KUTTERER, M. MAYER (1998). *The SCAR GPS campaigns: Accurate geodetic reference in Antarctica*. In R. Forsberg, M. Feissel, R. Dietrich (Eds.), *Geodesy on the move – gravity, geoid, geodynamics and Antarctica*. Volume 119 of Springer Series of IAG Symposia, pp. 474-479. Springer.
- DIETRICH, R. G. LIEBSCH (2000). *Zur Variabilität des Meeresspiegels an der Küste von Mecklenburg-Vorpommern*. *Zeitschrift für geologische Wissenschaften* 28(6), 615-623.
- DIETRICH, R., R. METZIG, W. KORTH, J. PERLT (1999). *Combined Use of Field Observations and SAR Interferometry to Study Ice Dynamics and Mass Balance in Dronning Maud Land*. *Polar Research* 18(2), 291-298. special issue: Proceedings of the Symposium on Polar Aspects of Global Change Tromsø, August 24-28 1998.
- DIETRICH, R., K. SHIBUYA, A. PÖTZSCH, T. OZAWA (2001). *Evidence for Tides in the Subglacial Lake Vostok, Antarctica*. *Geophys. Res. Letters* 28(15), 2971-2974.
- DREWES, H., W. BOSCH, K. KANIUTH (2002). *Erkennung und Verfolgung anomaler Meerwasserstände mit Altimetrie und Pegelregistrierungen im Nord-Atlantik (EVAMARIA)*. Schlussbericht des BMBF-Projekts 03F0193A, Munich.
- ENGELHARDT, G., P. GABENSKI, K. VASSILEVA (2000). *Zur Ableitung von Bewegungsparametern im Referenznetz Antarktis – Die Lösung des Bundesamtes für Kartographie und Geodäsie unter Nutzung der Berner GPS-Auswertesoftware*. In R. Dietrich (Ed.), *Deutsche Beiträge zu GPS-Kampagnen des Scientific Committee on Antarctic Research (SCAR) 1995-1998*, pp. 69-76. DGK, Reihe B, Heft Nr. 310, München.
- ESSELBORN, S. (2001). *Meereshöhen und ozeanische Zirkulation im Nordatlantik zwischen 1992 und 1998 – Eine Radar-altimeter-Studie*. Dissertation, 143 pp.
- ESSELBORN, S., R. CHENEY, L. MILLER (1999). *Changes of the Geostrophic Surface Circulation in the North Atlantic Related to the North Atlantic Oscillation as measured by Satellite Altimetry*. *IEEE Proc. IGARSS'99*, pp. 2007-2009.
- ESSELBORN, S. C. EDEN (2001). *Sea Surface Height changes in the North Atlantic Ocean Related to the North Atlantic Oscillation*. *Geophys. Res. Letters* 28, 3473-3476.
- ESSELBORN, S., L. MILLER, R. CHENEY (2001). *Heat Storage in the North Atlantic Ocean between 1992 and 1998 as estimated by satellite altimetry*. GKSS-report 2001/31, 76-80.
- FENOGLIO-MARC, L. (2001a). *Analysis and representation of regional sea level variability from altimetry and atmospheric data*. *Geophysical Journal International* 145(1), 1-18.
- FENOGLIO-MARC, L. (2001b). *Multi-mission altimetry data analysis and unification in the Mediterranean Sea*. ERS-ENVISAT Symposium Proceedings, ESA SP-461 (CD-Rom).
- FENOGLIO-MARC, L. (2002a). *Long-term sea level change in the Ionian Sea*. TUD/IPG/Alt Internal Report N.3.
- FENOGLIO-MARC, L. (2002b). *Long-term sea level change in the Mediterranean Sea from multi-satellite altimetry and tide gauge stations*. *Physics and Chemistry of the Earth* 27, 1419-1431.
- FENOGLIO-MARC, L. (2002c). *Sea level variability in Tropical Pacific 1992-1999*. TUD/IPG/Alt Internal Report N.2.
- FENOGLIO-MARC, L., E. GROTEN (2002a). *Local improvement of the marine geoid using altimetry data*. submitted to 'Cahiers of EGS', Proceedings of Workshop on Analytical Representation of Potential Field Anomalies for Europe.
- FENOGLIO-MARC, L., E. GROTEN (2002b). *Modelling the sea level variation for the unification of altimetric missions*. *Adv. Space Res.* 30(11), 2357-2362.
- FENOGLIO-MARC, L., E. GROTEN (2003). *On the variability of mean sea level*. *Allgemeine Vermessungs-Nachrichten*, 2/2000, Wichmann, 55-59.
- FENOGLIO-MARC, L., M. MARTINEZ-GARCIA (2001). *Sea level trends in the Mediterranean Sea from satellite altimetry and tide gauge stations*. In Proceedings of Final Workshop of Cost Action 40. *Sea level in Europe: Observation, Interpretation and Exploitation*, pp. 114-117. Hydrographic Institute of the Republic of Croatia, Split.
- FENOGLIO-MARC, L., Y. WANG, E. GROTEN (2000). *Investigation at regional scales of sea level variability at low and medium frequencies*. *AVISO Newsletter* (7), 40-43.
- FORBERG, M., M. POHL, H.-W. SCHENKE, T. SCHÖNE (2000). *GPS und Pegelmessungen in der Antarktis – Ein Beitrag zum einheitlichen Höhendatum*. In R. Dietrich (Ed.), *Deutsche Beiträge zu GPS-Kampagnen des Scientific Committee on Antarctic Research (SCAR) 1995-1998*, pp. 207-210. DGK, Reihe B, Heft Nr. 310, München.
- GROTEN, E., L. FENOGLIO, L. WANG (2000). *El Nino 1997 – main characteristics and interannual earth rotation variability*. *Allgemeine Vermessungs-Nachrichten*, 4/2000, Wichmann, 140-146.
- GRUBER, T., C. REIGBER, J. WÜNSCH (2000). *Estimation of ocean mass redistribution by means of altimetry and circulation models and its impact on the gravity field*. In R. Rummel, H. Drewes, W. Bosch, H. Hornik (Eds.), *IAG Section II Symposium: Towards an Integrated Global Geodetic Observing System (IGGOS)*, Volume 120 of Springer Series of IAG Symposia, pp. 218-221. Springer.
- HÄFELE, P., S. HUBER, K. KANIUTH (2002). *Vertical crustal movements of tide gauge sites around the North Atlantic Ocean*. In H. Drewes, A. Dodson, L. Fortes, L. Sánchez, P. Sandoval (Eds.), *Vertical Reference Systems*, Volume 124 of Springer Series of IAG Symposia, pp. 244-248.
- HAGEDOORN, J. D. WOLF (2003). *Pleistocene and Recent deglaciation in Svalbard: implications for tide-gauge, GPS and VLBI measurements*. *J. Geodyn.* (in press).
- HELM, A., A. BRAUN, S. EICKSCHEN, T. SCHÖNE (2002). *Calibration of the Shuttle Radar Topography Mission X-SAR Instrument Using a Synthetic Altimetry Data Model*. *Canadian Journal of Remote Sensing* 28(4), 573-580.
- HÖPFNER, J. (1999). *Interannual variations in length-of-day atmospheric-angular-momentum with respect to ENSO cycles*. *GeoForschungsZentrum Potsdam, STR99/07*, Scientific Technical Report, 22 pp.
- HÖPFNER, J. (2001a). *Atmospheric, oceanic hydrological contributions to seasonal variations in length of day*. *Journal of Geodesy* 75, 137-150.
- HÖPFNER, J. (2001b). *Interannual variations in length of day atmospheric angular momentum with respect to ENSO cycles*. *Zeitschrift für Vermessungswesen* 126(1), 39-49.
- HOWIND, J., M. BÖHRINGER, M. MAYER, H. KUTTERER, K. LINDNER, B. HECK (2000). *Korrelationsstudien bei GPS-Phasenbeobachtungen*. In R. Dietrich (Ed.), *Deutsche Bei-*

- träge zu GPS-Kampagnen des Scientific Committee on Antarctic Research (SCAR) 1995-1998, pp. 201-206. DGK, Reihe B, Heft Nr. 310, München.
- HUYBRECHTS, P. (2001). *Changes of the polar ice sheets*. In J. Lozan, H. Graßl, P. Hupfer (Eds.), *Climate of the 21st century: changes and risks*, pp. 221-226. GEO Wissenschaftliche Auswertungen (Hamburg).
- HUYBRECHTS, P. (2002). *Sea-level changes at the LGM from ice-dynamic reconstructions of the Greenland and Antarctic ice sheets during the glacial cycles*. *Quaternary Science Reviews* 21(1-3), 203-231.
- IHDE, J., J. ECK, U. SCHIRMER (2002). *A Digital Terrain Ice Model of Antarctica derived by ERS Radar Altimeter Data*. presented at XXVII SCAR Meeting, Shanghai, China, 14-17 July 2002. CD-ROM.
- JOCHMANN, H. (2002). *Die ozeanische Erregerfunktion, abgeleitet aus Altimeterdaten*. In H. Schuh, M. Soffel, H. Hornik (Eds.), *Vorträge beim 4. DFG-Rundgespräch im Rahmen des "Forschungsvorhabens Rotation der Erde" zum Thema "Wechselwirkungen im System Erde"*, Volume 118 of Deutsche Geodätische Kommission, Reihe A, pp. 125-127. Höllenstein/Wetzell, 8.-9. März 2001.
- KORTH, W., J. PERLT, R. DIETRICH (2000). *Ergebnisse geodätisch-glaziologischer Feldarbeiten während der Expedition 1998 in der Region der Schirmacheroase*. In R. Dietrich (Ed.), *Deutsche Beiträge zu GPS-Kampagnen des Scientific Committee on Antarctic Research (SCAR) 1995-1998*, pp. 219-227. DGK, Reihe B, Heft Nr. 310, München.
- KUHN, M. (2002). *Geoid variations due to mean sea level variations*. In H. Drewes, A. Dodson, L. Fortes, L. Sánchez, P. Sandoval (Eds.), *Vertical Reference Systems*, Volume 124 of Springer Series of IAG Symposia, pp. 282-290.
- KUHN, M., W. BOSCH, R. KANIUTH (2002). *Sea level variations in the North Atlantic*. In J. Adam, K.-P. Schwarz (Eds.), *Vistas for Geodesy in the New Millennium*, Volume 125 of Springer Series of IAG Symposia, pp. 487-492.
- LE MEUR, E., P. HUYBRECHTS (2001). *A model computation of the temporal changes of surface gravity and geoidal signal induced by the evolving Greenland ice sheet*. *Geophysical Journal International* 145, 835-849.
- LIEBSCH, G., R. DIETRICH (1998). *Sea level monitoring in the southern Baltic Sea: From tide pole to altimetry*. In P. Fell, M. Kumar, G. Maul, G. Seeber (Eds.), *Proceedings of the International Symposium on Marine Positioning (INSMAP98)*. Melbourne FL, USA, November 30 – December 4, 1998, pp. 154-166.
- LIEBSCH, G., R. DIETRICH (2000). *Validation of TOPEX/POSEIDON measurements in the southern Baltic Sea*. In R. Rummel, H. Drewes, W. Bosch, H. Hornik (Eds.), *IAG Section II Symposium: Towards an Integrated Global Geodetic Observing System (IGGOS)*, Volume 120 of Springer Series of IAG Symposia, pp. 145-149. Springer.
- LIEBSCH, G., R. DIETRICH, L. BALLANI, G. LANGER (2000). *Die Reduktion langjähriger Wasserstandsmessungen an der Küste Mecklenburg-Vorpommerns auf das Höhensystem HN76*. *Die Küste* 62, 3-28.
- LIEBSCH, G., R. DIETRICH, S. HALBFASS (1999). *Determination of heights and height changes in the Baltic Sea region using the Baltic Sea Level GPS Campaigns 1993 and 1997*. In M. Poutanen and J. Kakkuri (Eds.), *Final Results of the Baltic Sea Level 1997 GPS Campaign*, pp. 159-177. Reports of the Finnish Geodetic Institute, 99:4.
- LIEBSCH, G., K. NOVOTNY, R. DIETRICH, C. SHUM (2002). *Comparison of multi-mission altimetric sea-surface heights with tide gauge observations in the southern Baltic Sea*. *Marine Geodesy* 25(3), 213-234.
- LINDNER, K., M. MAYER, H. KUTTERER, B. HECK (2000). *Die Vermarkung der Netzpunkte – eine Bestandsaufnahme*. In R. Dietrich (Ed.), *Deutsche Beiträge zu GPS-Kampagnen des Scientific Committee on Antarctic Research (SCAR) 1995-1998*, pp. 27-30. DGK, Reihe B, Heft Nr. 310, München.
- MAYER, M., K. LINDNER, H. KUTTERER, B. HECK (2000a). *Deformationsanalyse zur Aufdeckung von Punkt- und Blockbewegungen im Bereich der Antarktischen Halbinsel*. In R. Dietrich (Ed.), *Deutsche Beiträge zu GPS-Kampagnen des Scientific Committee on Antarctic Research (SCAR) 1995-1998*, pp. 127-144. DGK, Reihe B, Heft Nr. 310, München.
- MAYER, M., K. LINDNER, H. KUTTERER, B. HECK (2000b). *Eine Strategie zur Ermittlung hochgenauer Koordinaten und Bewegungsraten im ITRF96 unter Verwendung der Berner GPS-Software Version 4.0*. In R. Dietrich (Ed.), *Deutsche Beiträge zu GPS-Kampagnen des Scientific Committee on Antarctic Research (SCAR) 1995-1998*, pp. 59-68. DGK, Reihe B, Heft Nr. 310, München.
- MENGE, C., G. SEEBER (2000a). *Untersuchungen und Beiträge zur Problematik der Phasenzentrumsvariationen von GPS Antennen*. In R. Dietrich (Ed.), *Deutsche Beiträge zu GPS-Kampagnen des Scientific Committee on Antarctic Research (SCAR) 1995-1998*, pp. 181-194. DGK, Reihe B, Heft Nr. 310, München.
- MENGE, F., G. SEEBER (2000b). *Auswertung der SCAR GPS Kampagnen mit GEONAP*. In R. Dietrich (Ed.), *Deutsche Beiträge zu GPS-Kampagnen des Scientific Committee on Antarctic Research (SCAR) 1995-1998*, pp. 77-90. DGK, Reihe B, Heft Nr. 310, München.
- MENGE, F., C. VÖLKSEN, G. SEEBER (2000). *Analyse von SCAR GPS Epochen- und Permanentstationsdaten aus der Antarktis mit GIPSY/OASIS-II*. In R. Dietrich (Ed.), *Deutsche Beiträge zu GPS-Kampagnen des Scientific Committee on Antarctic Research (SCAR) 1995-1998*, pp. 91-108. DGK, Reihe B, Heft Nr. 310, München.
- METZIG, R., R. DACH, R. DIETRICH, R. HARTMANN, W. KORTH, J. PERLT, W. WINZER (1998). *ERS-1&2 tandem mission InSAR data of Antarctica – glaciological application and assessment of accuracy*. In: EGS, *Annales Geophysicae*, Part I: Society Symposia, Solid Earth, Geophysics & Geodesy, Suppl. I to Vol. 16, p. C365, 1998.
- METZIG, R., R. DIETRICH, W. KORTH, J. PERLT, R. HARTMANN, W. WINZER (2000). *Horizontal ice velocity estimation and grounding zone detection in the surroundings of Schirmacheroase, Antarctica, using SAR interferometry*. *Polarforschung* 67(1/2), 7-14.
- MÜLLER, C. (2000a). *Seismische Anisotropie in Antarktika*. In R. Dietrich (Ed.), *Deutsche Beiträge zu GPS-Kampagnen des Scientific Committee on Antarctic Research (SCAR) 1995-1998*, pp. 163-180. DGK, Reihe B, Heft Nr. 310, München.
- MÜLLER, C. (2000b). *Seismotektonik in den Bereichen der Antarktischen Halbinsel, des Scotia und Weddell Meeres*. In R. Dietrich (Ed.), *Deutsche Beiträge zu GPS-Kampagnen des Scientific Committee on Antarctic Research (SCAR) 1995-1998*, pp. 155-162. DGK, Reihe B, Heft Nr. 310, München.

- NIEMEIER, W., M. RENNEN, H. SALBACH (2000). *Bestimmung regionaler und globaler Deformationen im Bereich der Antarktischen Halbinsel*. In R. Dietrich (Ed.), Deutsche Beiträge zu GPS-Kampagnen des Scientific Committee on Antarctic Research (SCAR) 1995-1998, pp. 109-126. DGK, Reihe B, Heft Nr. 310, München.
- NOVOTNY, K., G. LIEBSCH, R. DIETRICH, A. LEHMANN (2002). *Sea-level variations in the Baltic Sea: Consistency of geodetic observations and oceanographic models*. In J. Adam, K.-P. Schwarz (Eds.), *Vistas for Geodesy in the New Millennium*, Volume 125 of Springer Series of IAG Symposia, pp. 493-498. Springer.
- PÖTZSCH, A., B. LEGRESY, W. KORTH, R. DIETRICH (2000). *Glaciological Investigation of Mertz Glacier, East Antarctica, using SAR Interferometry and Field Observations*. Proceedings of ERS – ENVISAT Symposium, Gothenburg, 16-20 October 2000, ESA Publication SP-461.
- REIGBER, C., F. BARTHELMES, H. GREINER-MAI, T. GRUBER, H. JOCHMANN, J. WÜNSCH (1999). *Temporal gravity field variations from oceanic, atmospheric and inner core mass redistributions and their sensitivity to new gravity missions CHAMP and GRACE*. *Bollettino di Geofisica Teorica ed Applicata* 40(3-4), 329-340.
- REIGBER, C., A. BRAUN, H. MILLER, H. VON STORCH, D. WOLF (2001). *SEAL: Sea Level Change – An Integrated Approach to its Quantification*. EGS General Assembly 2001, Nice, 25-30 March 2001.
- RENTSCH, M., A. BRAUN, A. HELM, T. SCHÖNE (2000). *Operational Altimetry at GFZ – From ERS-2 to Envisat*. ESA – ERS/ENVISAT Symposium, Gothenburg, Sweden, October 2000., Abstract volume.
- RIEDEL, B. (2002a). *The elastic behaviour of Ekströmisen grounding zone*. Report No. 15 of Filchner-Ronne-Ice Shelf Programme, Alfred-Wegener-Institut für Polar und Meeresforschung, Bremerhaven.
- RIEDEL, B. (2002b). *Modelle zur Beschreibung des gezeitenbedingten Bewegungsverhaltens von Schelfeis in der Übergangszone*. Dissertation, Geodätische Schriftenreihe der TU Braunschweig, Heft 17.
- RIEDEL, B., B. NIXDORF, M. HEINERT, A. ECKSTALLER, C. MAYER (1999). *The response of the Ekström Ice Shelf in the grounding zone to tidal forcing*. *Annals of Glaciology* (29).
- SCHÖNE, T., A. BRAUN, C. REIGBER (2001a). *Altimetrie und Meeresspiegel – Möglichkeiten und Grenzen der Beobachtung*. Zürich, GAIA 10(3), 226-229.
- SCHÖNE, T., A. BRAUN, C. REIGBER (2001b). *Kontinuierliche Überwachung von Pegelstationen und GPS Hochseebojen*. Deutscher Hydrographentag 2001, Potsdam.
- SCHÖNE, T., A. BRAUN, M. RENTSCH, C. SHUM, C. REIGBER (2000). *Concept for using GPS-buoys for Radar Altimetry drift monitoring*. ESA ERS/ENVISAT Symposium, 16.-20. Oct 2000, Gothenburg, Sweden.
- SCHÖNE, T., S. EICKSCHEN (2000). *Wind Speed and SWH Calibration for Radar Altimetry in the North Sea*. ESA – ERS/ENVISAT Symposium, Gothenburg, Sweden, October, 2000, Abstract volume.
- SCHÖNE, T., M. POHL, H. SCHENKE (1999). *GPS and Tide Gauge Measurements: A Contribution for the Vertical Datum Determination in Antarctica*. In P. Fell, M. Kumar, G. Maul, G. Seeber (Eds.), *Proceedings of the International Symposium on Marine Positioning (INSMAP98)*, pp.303-310.
- SCHÖNE, T., G. UDINTSEV, H.-W. SCHENKE, M. FORBERG, M. POHL (2000). *Verlauf der Forschungsfahrt der "Akademik Boris Petrov" während GAP98*. In R. Dietrich (Ed.), Deutsche Beiträge zu GPS-Kampagnen des Scientific Committee on Antarctic Research (SCAR) 1995-1998, pp. 21-26. DGK, Reihe B, Heft Nr. 310, München.
- VEIT, A., H. MILLER (2000). *Geochemische Charakterisierung des pliozänen/pleistozänen Vulkanismus beiderseits der Bransfield-Strasse – Ein Beitrag zur plattentektonischen Situation an der Nordspitze der Antarktischen Halbinsel*. In R. Dietrich (Ed.), Deutsche Beiträge zu GPS-Kampagnen des Scientific Committee on Antarctic Research (SCAR) 1995-1998, pp. 145-154. DGK, Reihe B, Heft Nr. 310, München.
- WOLF, D., J. HAGEDOORN, M. THOMA, A. BRAUN (2000). *Pleistocene and recent changes of glaciation in Svalbard: implications for tide-gauge measurements*. 2000 Fall Meeting, American Geophysical Union, Eos. Transactions, Supplement, 81, F9-F10.
- WÜNSCH, J. (1999). *Oceanic influence on the seasonal polar motion*. *GeoForschungsZentrum Potsdam, STR99/10*, Scientific Technical Report, 18 pp.
- WÜNSCH, J. (2000). *Oceanic influence on the annual polar motion*. *Journal of Geodynamics* 30, 389-399.
- WÜNSCH, J. (2002a). *Der saisonale Zyklus in der Polbewegung unter spezieller Berücksichtigung des Ozeans*. In H. Schuh, M. Soffel, H. Hornik (Eds.), *Vorträge beim 4. DFG-Rundgespräch im Rahmen des "Forschungsvorhabens Rotation der Erde" zum Thema "Wechselwirkungen im System Erde"*, Volume 118 of Deutsche Geodätische Kommission, Reihe A, pp. 109-116. Höllenstein/Wetzell, 8.-9. März 2001.
- WÜNSCH, J. (2002b). *Oceanic and soil moisture contributions to seasonal polar motion*. *Journal of Geodynamics* 33, 269-280.

Earth Rotation

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1. National cooperation under the umbrella of DFG

German geodesists and other geoscientists have a fruitful cooperation in the field of earth rotation studies. A lot of coordinated research projects have been supported by the German research funding organization DFG (Deutsche Forschungsgemeinschaft) for more than twelve years. The participating scientists met for round table discussions near the fundamental station at Wettzell every two or three years, the last times in March 2001 and April 2003. The scientific papers presented at the meetings were regularly published (for example SCHUH, SOFFEL, HORNIK, 2002).

At the end of the first phase of cooperation in 2001, it was clear that there is still a great need for further research, especially concerning the interaction of earth rotation and other geodynamic processes in the earth system. Therefore a working group has composed a hundred-page conception paper "Earth rotation and global dynamic processes" (in German; SCHUH, DILL et al., 2003), which gives a detailed overview of the theoretical and observational foundations of earth rotation studies, a review of the present state of modelling and observation and a specification of the research work which shall be done in the next few years. This paper will serve as a framework for future research projects to be funded by the DFG.

2. Theory of earth rotation

2.1 Fundamentals and general studies

An outline of the variety of open questions and unsolved problems in the theory of earth rotation on the threshold of the new millennium was given by GROTEN (1999).

Different approaches for modelling the rotation of the earth within the framework of Newtonian mechanics and Einstein's gravitation theory were discussed by SOFFEL et al. (2002). BRUMBERG and GROTEN (2001) dealt with the earth rotation vector in the geocentric celestial reference system. The connection of the observed rotation vector and its theoretical counterpart from a dynamic-earth rotation theory is derived by transformations between different reference systems in the framework of general relativity.

The rigid earth nutation model H96NUT was presented by HARTMANN et al. (1999). Containing 699 terms, it is based on the tidal potential developed by HARTMANN and WENZEL and takes into account the torques exerted by the moon, the

sun and the planets on the triaxial earth with third and fourth order zonal gravity coefficients. The analytical computation method, which was independently established, yields a good agreement with the nutation series by Roosbeek and Dehant.

The problem of nutation and its transfer function in the framework of relativity was discussed by SOFFEL and KLIONER (1999). They showed that, according to the current way to derive transfer functions, the correction for geodetic precession has to be applied before that for the geodetic nutation.

A gyroscopic model of the earth was set up by SEITZ (and KUTTERER) (2002). They numerically solved the non-linear Liouville equation based on a triaxial inertia tensor of the solid earth and using model data of atmospheric and oceanic motions as well as lunisolar torques. The comparison of the results yields a good coincidence with IERS data. For the length of day, the correlation is 99% during a time span of four years.

The implementation of the IAU 2000 resolutions has an impact on products of the IERS. ROTHACHER (2000) reviewed which products are affected by which resolution. Mostly affected are the earth rotation parameters by the new precession/nutation model and by the new parametrization of the earth rotation matrix involving the celestial and the terrestrial ephemeris origin. ROTHACHER made therefore suggestions which parameters could in future be provided by the IERS.

2.2 Atmospheric, oceanic and other geophysical influences

A comparison of angular momentum functions of the atmosphere, ocean and ocean tides with observed series of the length of day and polar motion was given by SCHMITZ-HÜBSCH and DILL (2001). Their wavelet scalograms suggest that the amplitude of annual polar motion reacts on mass redistributions in the atmosphere and the ocean with a delay of up to one year. In addition, certain hydrological mass redistributions were investigated. Ground water variations cause a polar motion component with an amplitude of 30 – 70 mas and a length of day variation of up to 0.1 ms, whereas the influence of snow covering and of artificial alterations of the continental water distribution are much smaller.

HÖPFNER (2000 a) presented a detailed comparison of seasonal length-of-day changes and the atmospherical axial

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angular momentum. He analysed LOD time series from three institutions and atmospheric angular momentum time series from four meteorological centres, both filtered for annual and semi-annual frequencies. The atmospheric angular momentum series differ in the order of 0.03 ms for both frequencies. The differences between the various LOD series on one side and the various atmospheric angular momentum series on the other side are in the same order of magnitude for the annual frequency and approximately twice as large (and therefore very significant) for the semi-annual frequency, both with and without consideration of the inverted barometer effect. In a following study, HÖPFNER (2000 b, 2001 b) compared these discrepancies with other contributions to seasonal length-of-day changes, namely that of the high atmosphere wind term (which was not included in the previous analysis) and that of the ocean matter and motion terms. The time series were compressed to strict sine functions, which were parametrized by a single amplitude and phase angle, and supplemented by estimated parameters for the annual and semiannual contributions of hydrological angular momenta. In spite of considerable discrepancies in the basic data sets, the angular momentum budget turned out to be well balanced, with remaining differences in the order of 0.01 ms for both the annual and semi-annual frequencies.

The relations between the atmospheric axial angular momentum and the length of day on the interannual time scale were studied by HÖPFNER (1999, 2001 a). He compared length of day time series from the IERS, atmospheric angular momentum series from four meteorological centres and additionally a time series of the Southern Oscillation Index, all over a time span of almost four decades. All series were filtered to show only the variations at the biennial and lower frequencies, corresponding to the Quasi-Biennial Oscillation (QBO) and the El Niño Southern Oscillation (ENSO). For the ENSO, the signal parameters vary considerably; but the QBO signal turned out to be rather stable with an amplitude between 0.13 and 0.14 ms and a period between 650 and 900 days during the major part of the considered time span.

A comprehensive study of the influences of different geophysical processes (apart from seasonal atmospheric variations) on the rotation and the gravity field of the earth was given by JOCHMANN et al. (2001). Ocean dynamics and continental water storage were investigated as possible causes. Influences of the atmosphere and core dynamics were related to decadal periods of earth rotation parameters. Furthermore, the basic relations between physical processes and temporal variations of the gravity were discussed in order to infer some of these physical processes from gravity variations obtained by the modern satellite missions.

GREINER-MAI et al. (2000) computed the influence of inner-core motions on polar motion and the gravity field of the earth. A precessional motion of the figure axis of the ellipsoidal inner core, which is inferred from the geomagnetic dipole axis, causes a mass redistribution in the core of the earth and hence a variation of polar motion. These variations are similar to the decadal variations of observed polar motion. In an inverse approach, GREINER-MAI and

BARTHELMES (2001) derived the motion of the figure axis of the inner core from polar motion. Assuming that the part of decadal polar motion which cannot be explained by atmospheric variations must be caused by inner core motions, they derived the inner core excitation function from those of the observed polar motion and of the atmosphere and investigated how the figure axis of the inner core must change its direction so that the resulting mass redistribution causes this excitation function. The calculation suggests that the figure axis of the inner core has a mean tilt of 1ϕ and a mean eastward drift of 0.7ϕ per year and quasi-periodic decadal variations.

JOCHMANN and FELSMANN (2001) investigated the possible influence of inner core motions and atmospheric mass redistributions on long-periodic climate cycles in polar motion by comparing the Fourier spectra of the excitation functions computed from observed polar motion on the one hand and of time series of these geophysical processes on the other hand. They found partial coincidences at the periods of 11/13, 22/26, 30 and 83/90 years. But unique attributions were not possible due to the low quality of data and the lack of information on other geophysical effects. Jochmann (2002) computed the oceanic excitation function (matter part) of polar motion from satellite altimeter data (ERS1, TOPEX-POSEIDON) and related it to the excitation function of continental water storage.

WÜNSCH (1999, 2000) computed the seasonal oceanic excitation function of polar motion from four different ocean circulation models for twelve, six and four month periods and compared it with the excitation from observed polar motion, reduced for atmospheric excitation. The ocean model by Ponte et al. showed the best agreement. In WÜNSCH (2002 a,b), he extended his analysis by including also the inverse barometer effect, the soil moisture (five models) and the snow load. The NCEP/NCAR atmosphere reanalysis data, the ocean model by Ponte et al. and the rain and snow model by Chao and O'Connor almost completely close the annual balance of polar motion excitation with the IERS time series.

By a simultaneous simulation of the ocean tides and circulation (OMTC), THOMAS et al. (2000, 2001) estimated the oceanic excitation including the effects of nonlinear interactions between circulation and long-periodic tides, which were hitherto neglected in the usual linear superposition approach. They found that these second-order effects cause about 8% of the ocean-induced changes of the rotation of the earth. The contributions of the three oceans and their frequency dependence showed characteristic differences. More detailed presentations were given by THOMAS (2001, 2002). He considers thermohaline and wind-driven circulation, static and dynamic effects of the atmospheric pressure, the secondary potential due to the load and the self-attraction of the water masses and non-linear interactions and tides. This sequence of the mentioned effects corresponds to the estimated order of magnitude of their angular momentum functions.

The angular momentum variations of the atmosphere was analysed by STUCK and HENSE (2002) on the basis of their

global atmospheric circulation model ECHAM3, which is driven by observed sea surface temperatures and sea ice covering during the period 1949 – 1994. The spectral analysis of the simulated axial angular momentum yielded a coincidence of 80% with the observed length of day variations on the interannual time scale, whereas on the seasonal time scale the atmospheric model accounts only for 50% of the LOD variability. A combination with the model of ocean circulation and tides (OMTC) by Thomas gave a considerably better coincidence on both time scales. As for the equatorial component of the angular momentum, the contributions of the atmosphere and the ocean are nearly equal, and together they account for more than 50% of the observed variability at annual and longer periods. The intra-seasonal variability of polar motion is mainly caused by the mass component and the seasonal one by the motion component of the atmospheric and oceanic angular momenta.

The influence of secondary effects exerted by hydrological processes and deformations of the solid earth by surface loads was studied by DILL (2002 a,b). For computing mass shifts in the underground due to surface loads, he developed a model for the bend of the lithospheric plate involving Green functions as an alternative to Love surface numbers. By means of appropriate models for the respective direct effects and the indirect deformational effects, he simulated the influence of various hydrological processes: ground water variations, snow covering, the drying up of Lake Aral and the forthcoming filling of the Three Gorges Reservoir. Since the data of the mass shifts due to the natural hydrological effects are still insufficient and since the primary effects of the atmosphere and the ocean are still imperfectly modelled, these studies cannot yet contribute to a better modelling of earth rotation; but they lay the fundament for future work when improved input data of geophysical fluids will be available.

Diurnal and subdiurnal variations of polar motion and length of day were investigated by Arfa-Kaboodvand, Groten and co-authors (ARFA-KABOODVAND et al., 2000, 2002; LEVI et al., 2002). Their analysis of highly resolved GPS data by wavelet and partial correlation methods confirmed that the diurnal and semi-diurnal variations are predominantly caused by earth and ocean tides. They outlined a deterministic approach on the basis of the Liouville equation, which they deemed more appropriate for separating the different kinds of excitation.

3. Estimation of earth rotation parameters by different observation techniques

3.1 VLBI

Earth rotation parameters from simultaneous VLBI observations of different networks in 1997 – 1999 were computed and compared by TESMER (2002). The time series of polar motion and universal time showed significant offsets with respect to the IERS C04 series. A dependence of these parameters on the network configuration was also revealed by the analysis of one continuous observation series of five days, where one of the six telescopes dropped out on one day.

Short period variations in length of day and polar motion detected by VLBI between 1981 and 1999 were analysed by SCHUH and SCHMITZ-HÜBSCH (2000). By wavelet analysis of length-of-day series, they found periods of 28 days, 14 days down to 6.7 days, which are caused by lunisolar tides, and irregular quasi-periodic variations between 40 and 130 days, which are clearly correlated with the atmospheric angular momentum. On the subdiurnal time scale, periods between five and seven hours were found in universal time besides the diurnal and semi-diurnal periods.

TESMER et al. (2001) and KUTTERER and TESMER (2002, a,b) dealt with problems of parameter estimation and statistical analyses of subdiurnal earth rotation parameters from VLBI. Since subdiurnal estimates of terrestrial pole coordinates are necessarily highly correlated with simultaneous nutation parameter estimates, the latter were kept fixed. As numerical analyses of a CORE-A and a NEOS-A session shows, the accuracy of the pole coordinates and universal time depends not only on the observation geometry (stations and radio sources), but also on the temporal resolution level: the higher the resolution, the larger are the inaccuracy of the parameters and the correlations between consecutive parameters of the same kind.

STEINFORT and NOTHNAGEL (2002) described the method that is used to combine series of earth rotation parameters contributed by various VLBI analysis centres to one single ERP series and gave some numerical informations about the differences between the individual series and the combined one.

3.2 GPS

The lead of VLBI in determining subdaily polar motion and universal time as well as nutation corrections has largely been caught up by GPS. HEFTY, ROTHACHER et al. (2000) and ROTHACHER et al. (2001) dealt with daily and subdaily variations of polar motion and universal time, which are primarily induced by the ocean tides, on the basis of two-hour series produced by the CODE analysis centre of the International GPS service. In the first study, where the available earth rotation parameters cover the 420-day time span from April 1995 until June 1996, they found about twenty periodic terms in the diurnal and semi-diurnal frequency bands, ten of which could be identified as tidal periods. A comparison of the amplitudes and phase angles with other analyses from satellite altimetry, VLBI and SLR showed a good agreement for most of these periods, both for polar motion and universal time. In the extended second study, where the earth rotation parameters cover the three-year time span from January 1995 until February 1998, they identified even 57 tidal periods in polar motion and 41 ones in universal time. The comparison of the parameters with those from the other techniques showed mean square differences between 0.001 and 0.002 ms for the amplitudes of universal time and between 0.01 and 0.02 mas for the polar motion amplitudes.

As for estimating nutation corrections from GPS observations, WEBER, ROTHACHER et al. (2000) presented an update to a previous paper by themselves. From an extended set of daily nutation correction rates ranging from April 1994

until March 1999, they obtained nutation amplitude corrections of about twenty periods between 4.7 and 15 days in obliquity and longitude with respect to the IAU 1980 nutation model with standard deviations in both directions between 0.008 mas for the 4.7-day period and 0.025 mas for the 15-day period.

3.3 Laser gyroscopes

A new instrument type which allows direct measurements of the earth rotation vector is the laser gyroscope. A prototype was installed at Wettzell in 2000.

The properties of big ring lasers like the C-II (which is operated in New Zealand) and the measurement results that were achieved with the C-II were described by SCHREIBER et al. (1999, 2002, 2003).

KLÜGEL and SCHREIBER (2002) explained the local effects which can disturb the measurements, namely deformations of the instrument by temperature and air pressure variations as well as tilts of the instrument by local underground deformations, and they described the measures which were taken to minimize these effects.

4. Analysis of earth rotation parameters

4.1 Numerical investigations

HÖPFNER (2002 a,b) performed a detailed investigation of polar motion cycles based on the time series SPACE99 from the Jet Propulsion Laboratory ranging from 1976 until 2000. By band-pass filters he isolated individual series for the dominant Chandler and annual periods as well as for the secondary periods of 300 days, semi-Chandler, 6, 4, 3, 2 and 1.5 months. For each frequency band, he determined for every cycle of the pole the elliptic parameters: the semi-major and semiminor axes, the eccentricity, the direction of the semimajor axis and the period. For the annual polar motion, he found a distinct ellipticity with eccentricities of 0.2 – 0.5 and relatively stable directions of the principal axes. The Chandlerian polar motion, by contrast, has a much less distinct ellipticity with eccentricities of 0.0 – 0.2 and considerably changing directions of the principal axes, even for consecutive cycles. The polar motion components of the other frequency bands showed pronounced ellipticities with strongly instable parameters, some of them even changing their sense of revolution.

Finally he performed similar analyses for the Chandlerian and the annual components of polar motion separately for three long-time series ranging from the end of the 19th century until around 2000 and two series starting in the early sixties and the late seventies, respectively. The long-term variations of the amplitudes and periods became clearly visible. For the long-time series he also included a spectral analysis of the secular polar motion component (HÖPFNER, 2003).

Two of these long-time series of polar motion (IERS C01 and OA97/99 by Vondrak) were also analysed by SCHUH, RICHTER, NAGEL (2000) and SCHUH, NAGEL, SEITZ (2001). They estimated a secular linear drift of 3.3 mas per year in the direction of 76° western longitude. The variability of

periods and amplitudes of the Chandler and annual wobbles were investigated by sliding windows and wavelet methods.

Differences between universal time (UT) and atomic time could not be determined before the atomic time came into use in 1955. Before that, the only absolute time reference was ephemeris time (ET), which was realized by observations of lunar occultations. LIAO and GREINER-MAI (1999) calculated a length of day series that reaches back to 1892 by combining an old series of UT1 - ET and a modern series of UT1 - UTC. The IERS C04 series starts at 1962.0 although atomic time was kept since 1955. Therefore BIELE (2002) focussed on the time interval 1955.5 – 1962.0. He reviewed several UT1 data sets from that period and found that the latest re-reduction by Vondrak and Ron is the best one.

4.2 Wavelets and other modern theories applied for earth rotation

Observed time series of earth rotation parameters and geophysical excitation functions can be considered as stochastic processes. If the energy distribution varies with time, the traditional Fourier transform is not appropriate for signal analysis. That is why SCHMIDT (and SCHUH) (2000, 2001, 2002) presented a procedure which combines the wavelet theory with the theory of stochastic processes and thus makes it possible to analyse single time series and to compare different time series. This was demonstrated for time series of polar motion and length of day in connection with the atmospheric excitation functions.

A more detailed analysis of the IERS C04 series together with the atmospheric angular momentum function was presented by SCHMITZ-HÜBSCH (and SCHUH) (1999, 2002, 2003). The scalograms of the length of day series clearly showed the annual and semi-annual periods as well as the monthly and fortnightly periods and a period of seven days. The scalograms of polar motion (from which the Chandler wobble had been removed) showed clearly the annual wobble with a large prograde and a small retrograde component and a prograde semi-annual wobble. Frequencies below two months are quite irregular and contain as well retrograde as prograde parts.

Artificial neural networks were applied by (SCHUH,) ULRICH et al. (2002) for predicting earth orientation parameters. A comparison of the prediction error with other methods showed that for a short-term prediction of universal time this method is as good as others and that for time intervals of more than one hundred days it is even better.

References

- ARFA-KABOODVAND K., GROTEN E. (2002): *On high-frequency fluctuations of Earth's rotation and LOD*. In: Schuh et al. (2002), 63-69
- ARFA-KABOODVAND K., GROTEN E., VARGA P., ZAVOTI J. (2000): *Interpretation of high frequency polar motion and length of day variations*. In: Kolaczek, B.; Schuh, H.; Gambis, D. (eds.): *High frequency to subseasonal variations in Earth Rotation*. IERS Technical Note 28, 15-25

- BIELE J. (2002): *UT1 series 1955.5 – 1962.0 and their continuity*. In: Schuh et al. (2002), 77-86
- BRUMBERG V.A., GROTEN E. (2001): *A note on Earth's rotation angular velocity in the general-relativity framework*. Journal of Geodesy 75, 673-676
- DILL R. (2002 a): *Der Einfluss von Sekundäreffekten auf die Rotation der Erde*. Doctoral thesis, Technische Universität München. Deutsche Geodätische Kommission C 550
- DILL R. (2002 b): *Untersuchung hydrologischer Einflüsse auf die Rotation der Erde*. In: Schuh et al. (2002), 90-95
- GREINER-MAI H., BARTHELMES F. (2001): *Relative wobble of the Earth's inner core derived from polar motion and associated gravity variations*. Geophysical Journal International 144, 27-36
- GREINER-MAI H., JOCHMANN H., BARTHELMES F. (2000): *Influence of possible inner-core motions on polar motions and the gravity field*. Physics of the Earth and Planetary Interiors 117, 81-93
- GROTEN E. (1999): *Earth Rotation as a Geodesic Flow, a challenge beyond 2000?* In: Krumm, Friedhelm; Schwarze, Volker Siegfried (eds.): Quo vadis geodesia ...? – Festschrift for Erik W. Grafarend. Geodätisches Institut der Universität Stuttgart. 129-135
- HARTMANN T., SOFFEL M., RON C. (1999): *The geophysical approach towards the nutation of a rigid Earth*. Astronomy & Astrophysics Supplement Series 134, 271-286
- HEFTY J., ROTHACHER M., SPRINGER T., WEBER R., BEUTLER G. (2000): *Analysis of the first year of Earth rotation parameters with a sub-daily resolution gained at the CODE processing center of the IGS*. Journal of Geodesy 74, 479-487
- HÖPFNER J. (1999): *Interannual variations in Length-Of-Day and Atmospheric-Angular-Momentum with Respect to ENSO Cycles*. GeoForschungsZentrum Potsdam. Scientific Technical Report STR 99/07
- HÖPFNER J. (2000 a): *Seasonal length-of-day changes and atmospheric angular momentum oscillations in their temporal variability*. Journal of Geodesy 74, 335-358
- HÖPFNER J. (2000 b): *Atmospheric, oceanic and hydrological contributions to seasonal variations in length of day*. GeoForschungsZentrum Potsdam. Scientific Technical Report STR 00/05
- HÖPFNER J. (2001 a): *Interannual variations in length of day and atmospheric angular momentum with respect to ENSO cycles*. Zeitschrift für Vermessungswesen 126, 39-49
- HÖPFNER J. (2001 b): *Atmospheric, oceanic and hydrological contributions to seasonal variations in length of day*. Journal of Geodesy 75, 137-150
- HÖPFNER J. (2002 a): *Parameter variability of the observed polar motion with smaller amplitudes*. GeoForschungsZentrum Potsdam. Scientific Technical Report STR 02/01
- HÖPFNER J. (2002 b): *Parameter variability of the observed Chandler and annual wobbles based on space-geodetic measurements*. Zeitschrift für Vermessungswesen 127, 397-408
- HÖPFNER J. (2003): *Low-frequency variations, Chandler and annual wobbles of polar motion as observed over one century*. GeoForschungsZentrum Potsdam. Scientific Technical Report STR 03/01
- JOCHMANN H. (2002): *Die ozeanische Erregerfunktion, abgeleitet aus Altimeterdaten*. In: Schuh et al. (2002), 125-127
- JOCHMANN H., REIGBER C., GREINER-MAI H., WÜNSCH J., BARTHELMES F. (2001): *Geophysikalische Prozesse, Erdrotation und zeitlich variables Schwerfeld*. GeoForschungsZentrum Potsdam. Scientific Technical Report STR 01/11
- JOCHMANN H., FELSMANN E. (2001): *Evidence and cause of climate cycles in polar motion*. Journal of Geodesy 74, 711-719
- KLÜGEL T., SCHREIBER U. (2002): *Lokale Einflüsse auf inertielle Erdrotationssensoren*. In: Schuh et al. (2002), 128-132
- KUTTERER H., TESMER V. (2002 a): *Subdiurnal earth orientation parameters from VLBI networks – determinability and significance*. In: Adam, Jozsef; Schwarz, Klaus-Peter (eds.): Vistas for Geodesy in the New Millennium – IAG 2001 Scientific Assembly; September 2-7, 2001; Budapest, Hungary; International Association of Geodesy Symposia 125, 469-474
- KUTTERER H., TESMER V. (2002 b): *Statistical Assessment of Subdiurnal Earth Orientation Parameters from VLBI*. In: Vandenberg, Nancy R.; Baver, Karen D. (eds.): International VLBI Service for Geodesy and Astrometry – General Meeting Proceedings; February 4-7; Tsukuba, Japan. 272-276
- LEWIS E., ARFA-KABOODVAND K., GROTEN E. (2002): *Sub-diurnal variability of the earth's rotation – a second approach*. In: Schuh et al. (2002), 70-76
- ROTHACHER M. (2002): *Future IERS Products – Implementation of the IAU 2000 Resolutions*. In: Capitaine, Nicole; Gambis, Daniel; McCarthy, Dennis D.; Petit, Gérard; Ray, Jim; Richter, Bernd; Rothacher, Markus; Standish, Myles; Vondrak, Jan (eds.): Proceedings of the IERS Workshop on the Implementation of the New IAU Resolutions; 18-19 April 2002; Paris, France. IERS Technical Note 29, 77-84
- ROTHACHER M., BEUTLER G., WEBER R., HEFTY J. (2001): *High-frequency variations in Earth rotation from Global Positioning System data*. Journal of Geophysical Research 106 (B7), 13711-13738
- SCHMIDT M. (2001): *Wavelet-Analyse von Erdrotationsschwankungen*. Zeitschrift für Vermessungswesen 126, 94-100
- SCHMIDT M. (2002): *Wavelet-Analyse von Zeitreihen*. In: Schuh et al. (2002), 46-56
- SCHMIDT M., SCHUH H. (2000): *Abilities of wavelet analysis for investigating short-period variations of earth rotation*. In: Kolaczek, B.; Schuh, H.; Gambis, D. (eds): High frequency variations in Earth Rotation. IERS Technical Note 28, 73-80
- SCHMITZ-HÜBSCH H. (2002): *Wavelet-Analysen der Erdorientierungsparameter im hochfrequenten Bereich*. In: Schuh et al. (2002), 57-62
- SCHMITZ-HÜBSCH H., DILL R. (2001): *Atmosphärische, ozeanische und hydrologische Einflüsse auf die Erdrotation*. Zeitschrift für Vermessungswesen 126, 275-283
- SCHMITZ-HÜBSCH H., SCHUH H. (1999): *Seasonal and Short-Period Fluctuations of Earth Rotation Investigated by Wavelet Analysis*. In: Krumm, Friedhelm; Schwarze, Volker Siegfried (eds.): Quo vadis geodesia ...? – Festschrift for Erik W. Grafarend. Geodätisches Institut der Universität Stuttgart. 421-431

- SCHMITZ-HÜBSCH H., SCHUH H. (2003): *Seasonal and Short-Period Fluctuations of Earth Rotation Investigated by Wavelet Analysis*. In: Grafarend, Erik W.; Krumm, Friedrich W.; Schwarze, Volker S. (eds.): *Geodesy – The Challenge of the 3rd Millennium*. 125-134
- SCHREIBER U., KLÜGEL T., STEDMAN G.E., SCHLÜTER W. (2002): *Stabilitätsbetrachtungen für grosse Ringlaser*. In: Schuh et al. (2002), 156-158
- SCHREIBER U., SCHNEIDER M., STEDMAN G. E., ROWE C. H., SCHLÜTER W. (1999): *Charakterisierung des C-II Ringlasers*. In: Krumm, Friedrich; Schwarze, Volker Siegfried (eds.): *Quo vadis geodesia ...? – Festschrift für Erik W. Grafarend*. Geodätisches Institut der Universität Stuttgart. 433-438
- SCHREIBER U., SCHNEIDER M., STEDMAN G.E., ROWE C.H., SCHLÜTER W. (2003): *Characterisation of the C-II Ring Laser*. In: Grafarend, Erik W.; Krumm, Friedrich W.; Schwarze, Volker S. (eds.): *Geodesy – The Challenge of the 3rd Millennium*. 135-139
- SCHUH H., DILL R., GREINER-MAI H., KUTTERER H., MÜLLER J., NOTHNAGEL A., RICHTER B., ROTHACHER M., SCHREIBER U., SOFFEL M. (2003): *Konzeptpapier Erdrotation und globale dynamische Prozesse – Eine Übersicht über den derzeitigen Stand der Modellbildung, der Mess- und der Auswerteverfahren*. Will appear in the series *Mitteilungen des Bundesamtes für Kartographie und Geodäsie*
- SCHUH H., NAGEL S., SEITZ T. (2001): *Linear drift and periodic variations observed in long time series of polar motion*. *Journal of Geodesy* 74, 701-710
- SCHUH H., RICHTER B., NAGEL S. (2000): *Analysis of long time series of polar motion*. In: Dick, S.; McCarthy, D.; Luzum, B. (eds.): *Polar motion: historical and scientific problems*. IAU Colloquium 178; September 1999; Cagliari, Italy. 321-331
- SCHUH H., SCHMITZ-HÜBSCH H. (2000): *Short period variations in earth rotation as seen by VLBI*. *Surveys in Geophysics* 21, 499-520
- SCHUH H., SOFFEL M., HORNIK H. (eds.) (2002): *Vorträge beim 4. DFG-Rundgespräch im Rahmen des Forschungsvorhabens 'Rotation der Erde' zum Thema 'Wechselwirkungen im System Erde', Höllenstein/Wetzell, 08./09. März 2001*. Deutsche Geodätische Kommission A 118
- SCHUH H., ULRICH M., EGGER D., MÜLLER J., SCHWEGMANN W. (2002): *Prediction of Earth orientation parameters by artificial neural networks*. *Journal of Geodesy* 76, 247-258
- SEITZ F. (2002): *Atmosphärische und ozeanische Massenverlagerungen als Antrieb für ein Kreisellmodell der Erde*. In: Schuh et al. (2002) 96-101
- SEITZ F., KUTTERER H. (2002): *Numerical Solutions for the Non-Linear Liouville Equation*. In: Adam, Jozsef; Schwarz, Klaus-Peter (eds.): *Vistas for Geodesy in the New Millennium – IAG 2001 Scientific Assembly*; September 2-7, 2001; Budapest, Hungary. IAG Symposia 125, 463-468
- SOFFEL M., KLIONER S. (1999): *Nutation, transfer functions and relativity: relativistic nutation for a non-rigid earth*. In: Capitaine, N. (ed.): *Journ,es 1998 – Systèmes de référence spatio-temporels*; 21-23 septembre 1998; Paris, France. Observatoire de Paris. 79-85
- SOFFEL M., KLIONER S., XU C., WU X. (2002): *Erdrotation und Relativitätstheorie*. In: Schuh et al. (2002) 17-20
- STEINFORTH C., NOTHNAGEL A. (2002): *Rigorous Kombination von Erdrotationsparametern innerhalb des IVS*. In: Schuh et al. (2002), 28-33
- STUCK J., HENSE A. (2002): *Die simulierte dreidimensionale atmosphärische Drehimpulsvariabilität*. In: Schuh et al. (2002), 117-124
- TESMER V. (2002): *Untersuchung der mit VLBI gemessenen Erdrotationsparameter*. In: Schuh et al. (2002), 25-27
- TESMER V., KUTTERER H., RICHTER B., SCHUH H. (2001): *Reassessment of Highly Resolved EOP Determined with VLBI*. In: Behrend, Dirk; Rius, Antonio (eds.): *Proceedings of the 15th Working Meeting on European VLBI for Geodesy and Astrometry*; September 7-8, 2001; Barcelona, Spain. 83-90
- THOMAS M. (2001): *Ozeanisch induzierte Erdrotationsschwankungen – Ergebnisse eines Simulationsmodells für Zirkulation und ephemeridische Gezeiten im Weltozean*. Doctoral thesis, Fachbereich Geowissenschaften der Universität Hamburg
- THOMAS M. (2002): *Zur Simulation transienter Prozesse im Ozean und deren Einfluss auf die Erdrotation*. In: Schuh et al. (2002), 102-108
- THOMAS M., SÜNDERMANN J. (2000): *Numerical simulations of ocean induced variations of Earth's rotation*. In: Soffel, M.; Capitaine, N. (eds.): *Motion of Celestial Bodies, Astrometry and Astronomical Reference Frames – Journ,es 1999 & IX. Lohrmann-Kolloquium*, 167-169
- THOMAS M., SÜNDERMANN J., MAIER-REIMER E. (2001): *Consideration of ocean tides in an OGCM and impacts on subseasonal to decadal polar motion excitation*. *Geophysical Research Letters* 28, 2457-2460
- ULRICH M., SCHUH H., SCHWEGMANN W., EGGER D., MÜLLER J. (2002): *Vorhersage der Erdorientierungs-Parameter unter Verwendung künstlicher Neuronaler Netze*. In: Schuh et al. (2002), 87-89
- WEBER R., ROTHACHER M., BEUTLER G. (2000): *Contribution of GPS to monitor earth orientation parameters*. In: Kolaczek, B.; Schuh, H.; Gambis, D. (eds.): *High frequency to subseasonal variations in Earth Rotation*. IERS Technical Note 28, 43-51
- WÜNSCH J. (1999): *Oceanic Influence on the Seasonal Polar Motion*. GeoForschungsZentrum Potsdam. Scientific Technical Report STR 99/10
- WÜNSCH J. (2000): *Oceanic influence on the annual polar motion*. *Journal of Geodynamics* 30, 389-399
- WÜNSCH J. (2002 a): *Der saisonale Zyklus in der Polbewegung unter spezieller Berücksichtigung des Ozeans*. In: Schuh et al. (2002), 109-116
- WÜNSCH J. (2002 b): *Oceanic and soil moisture contributions to seasonal polar motion*. *Journal of Geodynamics* 33, 269-280

Additional bibliography made available after completion of the reports to Section V

- BAUCH A., ROTHACHER M., RUMMEL R.: *Bezugssysteme in Lage und Höhe: Tutorial zum Kursus Ingenieurvermessung 2000*, IAPG/FESG Schriftenreihe Nr. 7, München, 2000
- BEUTLER G., ROTHACHER M., KOUBA J., R. WEBER: *Polar Motion with Daily and Subdaily Time Resolution Polar Motion: Historical and Scientific Problems*, IAU Colloquium 178, Astronomical Society of the Pacific, San Francisco, 2000
- BEUTLER G., ROTHACHER M., DREWES H.: *Collocating Space Geodetic Networks: Scientific Rationale and State of Realization of the International Space Geodetic Network (ISGN)*. Proceedings of the International Workshop on Geodetic Measurements by the collocation of Space Techniques on Earth (GEMSTONE), 1-9, Tokyo, 1999
- DILL R. ROTHACHER M., THALLER D.: *Influence of the reference frame realization on earth rotation parameters*, Geophysical Research Abstracts: 27th EGS General Assembly, Vol. 4, Nice, 2002
- DILL R., ROTHACHER M.: *Comparison of EOP series from the IERS Analysis Campaign to align EOPs to ITRF2000/ICRF*, Geophysical Research Abstracts: EGS-AGU-EUG Joint Assembly, Vol. 5, Nice, 2003
- DUNN R.W., SHABALIN D.E., THIRKETTLE R.J., MACDONALD G.J., STEDMAN G.E., SCHREIBER K.U.: *Design and Initial Operation of a 367 m² rectangular ring laser*, Applied Optics, Vol. 41, No. 9, 1685-1688, 2002
- HEFTY J., ROTHACHER M., SPRINGER T., WEBER R., BEUTLER G.: *Analysis of the first Year of Earth Rotation Parameters with a Sub-Daily Resolution Gained at the IGS*, Journal of Geodesy, Vol. 74, 6479-487, Springer, 2000
- KLÜGEL T., SCHREIBER U.: *Lokale Einflüsse auf inertielle Erdrotationssensoren*, DGK- Mitteilungen, Reihe A, Heft 118, 128-132, 2002
- KOUBA J., BEUTLER G., ROTHACHER M.: *IGS Combined and Contributed Earth Rotation Parameter Solutions*, Polar Motion: Historical and Scientific Problems, IAU Colloquium 178, Vol. CS-208, Astronomical Society of the Pacific, San Francisco, 2000
- ROTHACHER M., BEUTLER G., HERRING T. A., WEBER R.: *Estimation of nutation using the Global Positioning System*, B 34835-4859, 1999
- ROTHACHER, M., BEUTLER G., HERRING T. A., WEBER R.: *Estimation of Nutation Using the Global Positioning System*, Journal of Geophysical Research, Vol. 104, B34835-4859, 1999
- ROTHACHER M., BEUTLER G., MA C., MACMILLAN D., WEBER R.: *Comparison of High-Frequency Earth Rotation Parameters from GPS and VLBI*, Geophysical Research Abstracts: 25th EGS General Assembly, Vol. 2, Nice, 2000
- ROTHACHER M.: *Earth rotation parameters from GPS and VLBI*, 33rd COSPAR Scientific Assembly, 81, Warsaw, 2000
- ROTHACHER M., WEBER R.: *Non-Tidal Signals in High-Frequency Earth Rotation Parameter Series*, Eos, Transactions, American Geophysical Union 2001 Fall Meeting, Vol. 82, 47F289, San Francisco, 2001
- ROTHACHER M., BEUTLER G., WEBER R., HEFTY J.: *High frequency variations in earth rotation from Global Positioning System Data*, Journal of Geophysical Research, Vol. 106, B713711-13738, 2001
- ROTHACHER M., WEBER M.: *Analysis of high-frequency earth rotation parameter series from GPS and VLBI*, IAG 2001 Scientific Assembly: Abstracts, 71-72, Budapest, 2001
- ROTHACHER M.: *Future IERS Products: Implementation of the IAU 2000 Resolutions*, Proceedings of the IERS Workshop on the Implementation of the New IAU Resolutions, 77-84, Verlag des Bundesamtes für Kartographie und Geodäsie, Frankfurt am Main, 2002
- ROTHACHER M., MÜLLER J., NÖTHNAGEL A., RICHTER B., SOFFEL M.: *Bezugssysteme und ihre Realisierung – Konzeptpapier Kapitel 4*, DFG-Rundgespräch, Höllenstein/Wetzell, 2003
- SCHREIBER U.: *Application of high precision ring laser gyroscopes*, Proceedings of the CRL International Symposium on Light Propagation and Sensing Technologies for Future Applications, 144-149, 2002
- SCHREIBER U., KLÜGEL T., STEDMAN G.E., SCHLÜTER W.: *Stabilitätsbetrachtungen für große Ringlaser*, DGK- Mitteilungen, Reihe A, Heft 118, 156-158, 2002
- SCHREIBER U., SCHNEIDER M., VELIKOSELTSEV A., STEDMAN G.E., SCHLÜTER W.: *Very large ring lasers*, Gyroscopy and Navigation, No 1 (36), 88-95, 2002
- WEBER R., ROTHACHER M., BEUTLER G.: *Contribution of the GPS to monitor Earth Rotation Parameters*, IERS Technical Note 28: High frequency to subseasonal variations in Earth Rotation, 43-51, Observatoire de Paris, Paris, 2000
- WEBER R., ROTHACHER M.: *The Quality of Subdaily Polar Motion Estimates Based on GPS Observations*, Polar Motion: Historical and Scientific Problems, IAU Colloquium 178, Astronomical Society of the Pacific, San Francisco, 2000
- WEBER R., ROTHACHER M.: *A Revised Set of Nutation Amplitudes Calculated From six Years of GPS Data*, Eos, Transactions, American Geophysical Union 2001 Fall Meeting, Vol. 82, 47F293, 2001