DEUTSCHE GEODÄTISCHE KOMMISSION

bei der Bayerischen Akademie der Wissenschaften

Reihe B Angewandte Geodäsie Heft Nr. 312

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

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ISSN 0065-5317 ISBN 3 7696 8589 X

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Der Druck dieser Veröffentlichung wurde aus Mitteln der Bayerischen Akademie der Wissenschaften gefördert
The printing of this volume was funded by the Bavarian Academy of Sciences

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ISSN 0065-5317 ISBN 3 7696 8589 X

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-probablistic 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)

Bernhard Heck
National Committee for Geodesy and Geophysics

Reinhard Rummel
Permanent Secretary of the German Geodetic Commission

Helmut Hornik
Secretary of the German Geodetic Commission

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SECTION I

POSITIONING

Positioning

– Overview and highlights –

J. IHDE[1]

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 GeoForschungsZentrum (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 laserscanning 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 introduces, 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 promissing 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 practicse.

Precise positioning on global and regional scales

J. IHDE[1], H. HABRICH[2], H. HORNIK[3], K. H. PAHLER[4], W. SCHLÜTER[5]

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 wich 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 Subcommission 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 form 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-Vallee 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 Normaals Amsterdams 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 all 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).

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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 Subcommission 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.

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Positioning for close range and engineering applications

W. NIEMEIER[1]

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 (KORITTKE & 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 determind 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 variing 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), MUCKE (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 derivated into two main steps

a) Estimation of of the geometric primitives, like edges, corners, plains 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), sherical 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 introduces, 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 equiped 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 firedamp-proof and the explosive-proof to make this IMS applicable in mining and in the interior of landfills.

The promissing 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 an 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 practitiniers 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 engineerings 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 on overview on current achievements and future developments in this more and more important field of application for positioning systems.

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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, SEEBER 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) .

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SECTION II

ADVANCED SPACE TECHNOLOGY

Advanced Space Technology
– Overview and highlights –

R. RUMMEL[1]

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/envrionment	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.

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Satellite gravity field missions

K.H. ILK[1], J. MÜLLER[2]

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.

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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 then 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 (MTLRS 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 Miltar, 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), DGFI (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 usefully 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 (CSAPLOVICS, 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.

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Atmosphere sounding using GPS radio occultation

J. WICKERT[1]

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 Minisatellite 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 simplify 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; WEHRENPFENNIG 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.

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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 Subcommission 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 Subcommission 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.

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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 stong 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 continuos, 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 Subcommission on Multi-Mission Satellite Altimetry (http://www.dgfi.badw.de/SCOMMSA). The subcommission discussed the establishment of an international altimeter service, IAS, as a core element of a global geodetic/geophysical 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 Januar 2003, and the upcoming Cryosat mission, to be launched in 2004, with a scanning altimeter mode both set up completely different requirement for the coss-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 auxillary 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 cross-overs 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. It 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 filed 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) synthetise 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. Therefore, 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 KLOKO¤NIK 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.

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SECTION III

DETERMINATION OF THE GRAVITY FIELD

Determination of the Gravity Field

– Overview and highlights –

G. BOEDECKER[1]

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-Pizetti 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 model*s (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

E. Groten[1], B. Richter[2], H. Wilmes[2]

G. Boedecker (Bayerische Kommission für die Internationale Erdmessung (BEK), München

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 Measures 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)

H.-J. Götze, Freie Universität Berlin

(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 (**M**ediciones **I**nternacionales de **Gr**avedad in los **A**ndes).

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 10^{-5} m/s^2 per day.

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

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

$FA = g_{abs} - (g_h + {}^*g_{top} + {}^*g_{Niv})$ *(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,

${}^*g_{top}$: terrain correction,

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

${}^*g_{bou}$: (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 kg/m^3 and 1 640 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 $^{-5}$ m/s^2 (flat areas) and 1.2 H 10 $^{-5}$ m/s^2 (in the Cordillera de Lipez and the recent volcanic arc of the Western Cordillera). Along the southern SALT traverse (38/ – 42º S; 72 / – 62/ 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 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} m/s^2, which is less than 1% of the overall magnitude of more than 450 H 10^{-5} 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} m/s^2, in the worst case we observed 0.94 10^{-5} 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} 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} 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 1.17H10^{-5} m/s^2 were obtained. At 40 reference stations we observed an average error of 0.28H10^{-5} 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.

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:

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 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 it's 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 (h2, l2) or amplitudes of typical diurnal and semi-diurnal periods can be derived from LLR data.

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Global Gravity Field Modelling

T. GRUBER[1]

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 a 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 canonball 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 el 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).

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Regional and local gravity field modelling

H. Denker[1]

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 Rappsilber, 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.

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SECTION IV

GENERAL THEORY AND METHODOLOGY

General Theory and Methodology
– Overview and highlights –

B. HECK[1]

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. JEKELI, 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 *Ausgleichungsrechnung* (*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. GRAFAREND[1]

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

- Special Cojmmission #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 cooperation. 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.

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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 2202b) 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 stochastical processes. A systematic extension of the theory of stochastical 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 (W0) 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 Lanszos 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.

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Stochastic methods of data evaluation

S. MEIER[1]

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 RENNER (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 RENNER (2000). Geometry analyses can also contribute to outlier testing or redundance 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 autocorrelations 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, stochastical 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).

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Non-stochastic methods of data evaluation

H. KUTTERER, M. SCHMIDT[1]

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-compactly 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 Kaiserlautern. 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 NiZo and La NiZa are identified. GROTEN et al. (2000) apply PCA to El NiZo and La NiZa 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.

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SECTION V

GEODYNAMICS

Geodynamics
– Overview and highlights –

H. DREWES[1]

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. AUGATH[1]

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, CAMPELL 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 GEODYSSEA.

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.

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Tidal and non-tidal gravity field variations

B. Richter[1]

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" (M^{3}CIS) 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 fur 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 nm s^{-2}/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 supple-

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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 (h2, l2) 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 Diizce (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.

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Sea Level and Ice Sheets

R. DIETRICH[1]

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 Carribean 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 Intercomparison 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).

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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 atmospherical 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, atmosperic 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 Ni¤o 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 dipol 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 atmoshpere 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 1ø and a mean eastward drift of 0.7ø 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. srrrhowed 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 intraseasonal 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 paramters contributed by various VLBI analysis centres to one single ERP series and gave some numerical informations about the differences between the individual sereis 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 semimajor 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 ellipicities 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 separatly 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 76ø 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.

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