**DEUTSCHE GEODÄTISCHE KOMMISSION**

**bei der Bayerischen Akademie der Wissenschaften**

**Reihe B** **Angewandte Geodäsie** **Heft Nr. 308**

# NATIONAL REPORT
# OF THE FEDERAL REPUBLIC OF GERMANY
# ON THE GEODETIC ACTIVITIES
# IN THE YEARS 1995 B 1999

**XXII General Assembly**
**of the International Union for Geodesy and Geophysics (IUGG)**
**1999 in Birmingham**

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

**München 1999**

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# Foreword

Every four years the General Assemblies of the *International Union of Geodesy and Geophysics (IUGG)* and of the *International Association of Geodesy (IAG)* provide an opportunity for taking a look back onto the developments in the field of geodesy. On the occasion of the XXII General Assembly of the IUGG which takes place from July 19-30, 1999 in Birmingham, UK, the *German Geodetic Commission (DGK)* presents the following report on the geodetic activities in the Federal Republic of Germany in the period from 1995 to 1999.

According to its bylaws the IAG is organized in five sections covering different aspects and topics in Geodesy.

- *Section I (Positioning)* concentrates on the positioning aspects in Geodesy, considering global and regional geodetic networks, applications in engineering, and marine positioning. Special emphasis has been given to GPS-related subjects (quality issues, active networks, advanced analysis, ambiguity resolution, site effects and atmospheric monitoring).
- *Section II (Advanced Space Technology)* studies the use of satellite techniques such as gravity gradiometry, satellite-to-satellite tracking, satellite and lunar laser ranging, satellite altimetry and SAR interferometry. Specific topics are related to the geodynamic WEGENER project, spaceborne atmospheric monitoring and the combination of multiple space techniques for precise orbit determination.
- *Section III (Determination of the Gravity Field)* is responsible for absolute and relative terrestrial gravimetry and the determination of the external gravity field and the (quasi-)geoid as well as for gravity networks and gravimetric data bases. Strong consideration is given to the assessment and refinement of global digital terrain models, kinematic gravimetry, as well as global and local gravity field modelling.
- *Section IV (General Theory and Methodology)* studies problems related to the modelling of geodetic observations in physical and mathematical respects and general aspects of data evaluation. Special emphasis is put on inverse problems, the use of wavelets in geodesy, dynamic isostasy and modelling of temporal changes of the gravity field.
- *Section V (Geodynamics)* deals with the determination of recent crustal movements and deformations, tides and other temporal variations of the gravity field, sea level and ice sheet variations as well as earth rotation variation and its geodynamic causes. Specific topics are geodetic contributions to understanding natural hazards, interactions of the atmosphere and the oceans with the earth's rotational dynamics, and geophysical interpretation of temporal geopotential variations.

The editors of this volume and the German Geodetic Commission acknowledge the work of all persons that have contributed to this report.

The financial and logistic support by the Bavarian Academy of Sciences for publishing and printing of this volume is highly appreciated.

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National Committee for Geodesy and Geophysics

Reinhard Rummel
Permanent Secretary of the German Geodetic Commission

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National Committee for Geodesy and Geophysics

Helmut Hornik
Secretary of the German Geodetic Commission

# Contents

# SECTION I

# POSITIONING

# Positioning
## Overview and highlights

H. DREWES

## Overview

The activities of German scientists and institutions in geodetic positioning during the time period 1995 to 1999 may be divided into (1) global and long range positioning, (2) permanent networks and real-time positioning, (3) close range and engineering applications. The following reports will be structured according to these subdivisions. German scientists contributed actively to the work of all the Section I bodies, which are:

- Commission X: Global and Regional Geodetic Networks, in particular in the Sub-Commission for Europe (EUREF) and in the SIRGAS Project for South America;
- Special Commission 4: Application of Geodesy to Engineering, with emphasis on the four Working Groups on (1) Mobile Multi-Sensor Systems, (2) Building Structures as Kinematic Systems, (3) High Precision Alignment Systems, (4) Geometrical Investigation of Spatial Geodetic Problems.

German scientists were involved as members in the Section I Special Study Groups

- SSG 1.154: Quality Issues in Real Time GPS Positioning,
- SSG 1.155: Active GPS Networks,
- SSG 1.156: Advanced GPS Analysis for Precise Positioning,
- SSG 1.157: GPS Ambiguity Resolution and Validation,
- SSG 1.158: GPS Antenna and Site Effects,
- SSG 1.159: Use of GPS Positioning from Atmospheric Monitoring.

Besides of these activities in positioning directly related to Section I, great efforts were performed by German institutions and scientists in positioning within the IAG Services: International Earth Rotation Service (IERS) realizing the IERS Terrestrial Reference Frame (ITRF), International GPS Service (IGS), International Laser Ranging Service (ILRS), and International VLBI Service for Geodesy and Astrometry (IVS). German institutions are acting in these services as observatories, data centers, analysis centers, and they are contributing to other product centers. Information on these services may be found in the reports of Sections II and V to which they are assigned in the present IAG structure. The outcoming of the investigations and research work, however, is also reflected in the above mentioned bodies of Section I and will therefore be reported here, too.

A lot of positioning activities are related to geodynamics projects in particular the networks for global plate kinematics and regional crustal deformations. These will be reported in detail in Section V but shall be mentioned here because of their scientific importance for modern developments of positioning methods. German institutions participated especially in actual projects in Europe (Mediterranean and Central Europe), Asia (GEODYSSEA, CATS) and South America (CASA, SAGA).

Modern positioning methods are nowadays dominated by advanced space techniques which will be reported in Section II, mainly by its Commission VIII CSTG. German institutions participated strongly in the PRARE project and the GLONASS experiment. Efforts have also been made in the study of new navigation systems such as GNSS and GALILEO.

The applications of positioning for engineering are closely related to the work performed within corresponding bodies of the International Federation of Surveyors (Fédération Internationale de Géomètres, FIG). Relevant developments and results for geodesy will be reported here.

## Highlights

The highlights of German contributions to geodetic positioning are certainly the observation and analysis activities in global and regional networks as well as in real time and kinematic positioning. Besides the practical aspects of position and velocity determinations by coordinates and their time derivatives, many theoretical research has been done in order to improve the mathematical and physical models and evaluation approaches.

In *global positioning* one has to mention explicitly the fundamental observational activities at the Wettzell observatory (Fundamentalstation Wettzell). This station is one of the best equipped sites of the world and is participating in all the existing IAG services using modern space techniques (VLBI, SLR, GPS, PRARE). Global data centers are managed by Bundesamt für Kartographie und Geodäsie (BKG) for the IVS and by Deutsches Geodätisches Forschungsinstitut (DGFI) for the ILRS. Acting as global analysis centers are Geo-

ForschungsZentrum Potsdam (GFZ) for the IGS, as well as BKG and the Geodetic Institute of the University of Bonn (GIUB) for the IVS.

In *regional positioning* we shall emphasize the activities of several German groups within the realization of the European Reference Frame (EUREF). BKG is working as a data center and, together with the Bayerische Kommission für die Internationale Erdmessung (BEK), as an analysis center. DGFI is acting as a data and analysis center for the South American Geocentric Reference System (Sistema de Referencia Geocéntrico para América del Sur, SIRGAS) and the corresponding IGS Regional Network Associate Analysis Center (RNAAC-SIR).

In *close range positioning*, a highlight is the installation of the German Satellite Positioning (SAPOS) network, a set of permanently observing GPS stations covering all Germany and mainly used for official and engineering surveying. It has recently been extended to real time and kinematic applications.

Precise *inertial techniques* as principally developed for navigation purposes are getting an increasing importance for positioning, in particular in its combination with differential GPS (DGPS). Sophisticated investigations have been performed on this topic by several German groups. The research includes the mathematical modelling as well as hardware equipment (e.g. for its use in airborne gravimetry). A variety of technical realizations has been studied and will be summarized in the following.

Altogether, a broad spectrum of applications of geodetic positioning has been investigated during the past four years, most of them – naturally – related to the GPS. A lot of new techniques have been developed that certainly will stimulate the future research on this field.

# Permanent GPS networks and realtime positioning

W. SCHLÜTER, K. PAHLER

## Introduction

In the period from 1995 to 1999 German institutions and scientists have placed a major contribution to the establishment of permanent active GPS-networks. Global, regional and national activities have been carried out in particular supporting

- the global network within the frame of IGS (International GPS Service) and CSTG (International Coordination of Space Techniques in Geodesy),
- the European network in the frame for EUREF (European Reference Frame),
- the national networks for federal requirements and for requirements of the states in the frame of SAPOS (Satelliten Positionierdienst der deutschen Landesvermessung).

These actions include the operation of permanent GPS-stations, by data centers and analysis centers and are capable to support the realtime applications.

The station operation, the data flow from the stations to data centers and the data analysis today are developed so far as a routine procedure, up to the provision of the products.

Beside the support of the GPS-networks, the GIBS (GPS Informations- und Beobachtungssystem), which provides actual information on the GPS- and GLONASS-system has been operated.

Investigations have been made on the determination of the phase center of GPS-antennas and on their variations.

## Activities within the IGS and CSTG

The German contributors to the activities of the IGS and CSTG are the GeoForschungsZentrum (GFZ) -Potsdam and the Bundesamt für Kartographie und Geodäsie (BKG) – former Institut für Angewandte Geodäsie (IfAG).

GFZ is operating the permanent GPS-stations (GALAS, REIGBER 1996)

- Potsdam/Germany
- Oberpfaffenhofen/Germany
- Zwenigorod/Russia
- Kitab/Usbekistan
- La Plata/Argentina.

BKG is operating the permanent GPS-stations

- O'Higgins/Antarctica (Turbo Rogue)
- Lhasa/Tibet-China(Turbo Rogue)
- Wettzell/Germany. (Turbo Rogue)

DGFI is operating permanent GPS stations in South-america.

One of the global analysis center for IGS is operated by GFZ. BKG serves as one of the regional data centers with the priority to hold and provide the data and products for Europe.

The work has been published in the IGS-Annual Reports and in the IGS-Workshop Proceedings (NEILAN et al. 1996, ZUMBERGE et al. 1995, ZUMBERGE et al. 1996, ZUMBERGE et al. 1997).

Within the frame of CSTG, the IGEX (International GLONASS Experiment) has been started in 1998. BKG supported the campaign by the provision of continuously operating ASHTECH Z18 receivers at Wettzell and at Reykjavik and a 3S Navigation receiver at Ankara. A tremendous effort has been made by BKG towards the integration of GLONASS data in the Bernese Software Package (HABRICH 1998). The effort finally results in the routinely handling of the GLONASS data for the evaluation of GLONASS orbits and station coordinates.

## Activities within EUREF perm.

While in the beginning of the decade EUREF has been established through GPS-campaigns collecting observations in epoch stations, the realisation and maintenance of EUREF today has been strongly supported by the operation of around 70 permanent GPS stations covering Europe (EUREF perm.). Some of the stations are identical with IGS-stations. More than 12 analysis centers are performing the daily data analysis. Each analysis center evaluates a subnetwork of EUREF perm. The combination of the results of these European analysis centers is routinely performed by the CODE (Center for Orbit Determination of Europe) at Bern. The BKG is supporting the European permanent network (EUREF-perm.) by the operation of permanent GPS receivers at

- Wettzell (Turbo Rogue, Ashtech Z12, Ashtech Z18 and TRIMBLE SSI),
- Lhasa, Tibet-China in cooperation with the National Bureau of Surveying and Mapping (Turbo Rogue),
- Reykjavik, Island in cooperation with Landmaelingar Islands (on the American Plate) (Turbo Rogue, Ashtech Z18),
- Höfn, Island in cooperation with Landmaelingar Islands (on the European Plate) (Ashtech Z12),
- Ankara, Turkey in cooperation with General Command of Mapping (Turbo Rogue),
- Nicosia, Cyprus in cooperation with Department of Lands and Survey on Cyprus (Turbo Rogue),

– Sofia, Bulgaria in cooperation with Bulgarian Military Topographic Service and the Laboratory of Geotechnics (Ashtech Z12),
– Zelenchukskaja, Russia in cooperation with Institut für Angewandte Astronomie, St. Petersburg (Turbo Rogue).

All the data from the European stations operated also by other agencies are collected at the BKG-data center in Frankfurt. The BKG acts as one of the data analysis centers for EUROPE. Since 1999 The University of Bern and BKG are combining the results of the different European analysis centers. The objective is, after the demonstration of identical results, that BKG will take over the routinely combination for EUREF-perm..

The work which has been carried out so fare is published in the Proceedings of the EUREF-Symposia held in Helsinki, Warsaw, Ankara and Ahrweiler (GUBLER et al. 1995, GUBLER et al. 1996, GUBLER et al. 1997) and (BRUYNINX et al. 1997, FRANKE et al. 1998, REINHART et al. 1997, REINHART et al. 1997, SCHLÜTER et al. 1996, SEEGER et al. 1997, SEEGER 1997, SEEGER et al. 1997, SEEGER et al. 1998, SEEGER et al. 1997, WEBER 1997, WEBER et al. 1997, WEBER et al. 1997, WEBER et al. 1997, WEBER et al. 1997, WEBER et al. 1996).

## National activities

Permanent GPS stations have been established in Germany by the federal state agencies such as BKG and BfG (Bundesamt für Gewässerkunde) and by the individual state-agencies in order to realise an active reference frame for positioning purposes all over Germany.

The federal agencies and the survey agencies of the 16 German states are cooperating within the AdV (Arbeitsgemeinschaft der Vermessungsverwaltung) for the establishment of the SAPOS – a multipurpose satellite positioning service.

SAPOS provides positioning services at different levels

1. real time DGPS at the level of ± 1 – 3 m (EPS), transmitting correction data via radio frequencies by employing RTCM2.0 format,
2. real time DGPS at the level of 1 – 5 cm (HEPS) transmitting correction data via 2 m band-transmitters employing RTCM2.1 format,
3. near real time positioning at the level of 1 cm in post-processing modus employing RINEX data transmitted via telephone or Inter-/Intranet (GPPS),
4. Geodetic high pression positioning better than 1 cm employing 24 h data in RINEX format in postprocessing mode by making use of the CODE-ephemeries (HGPS).

Currently more than 100 permanent GPS stations have been set up by the agencies, covering Germany in different densifications. Aiming in a homogeneous coverage more than 200 station will be established.

The permanent GPS stations are equipped with geodetic two frequency GPS-receivers, monitoring systems and data transmission systems (modems, telephones, radio transmitters) (BECKER M. et al. 1998, BECKERS et al. 1997, BEHRENS 1997, BEUL 1995, BEUL 1997, BOLJEN, 1998, DIERHOFF et al. 1996, DRAKEN 1996, ELSNER 1996, FRÖHLICH 1995, GRAEFF 1995, HANKEMEIER 1995, HANKEMEIER 1995, HANKEMEIER 1997, HANKEMEIER 1997, HANKEMEIER, HANKEMEIER et al. 1998, HANKEMEIER et al. 1998, IRSEN et al. 1996, JAHN 1996, JAHN 1997, KUHN et al. 1998, LEIPHOLZ 1997, PAHLER 1996, PATZSCHKE 1996, ROKAHR 1997, ROSENTHAL 1997, ROSENTHAL 1997, ROSSOL 1996, SEEGER et al. 1997, STOFFEL 1997, WANNINGER et al. 1998, WEBER et al. 1997, WIRTH 1997).

The real time DGPS-service (EPS) is realized by the state services in cooperation with the broadcasting agencies by making use of the RDS-channels in the fm-band. BKG in cooperation with the German Telekom is transmitting correction data from the permanent station "Mainflingen" via a low frequency transmitter in order to cover entire Germany (DIETRICH et al. 1997, DITTRICH et al. 1995, DITTRICH et al. 1995, ELSNER 1997, KÜHMSTEDT et al., LINDSTROT 1996, LINDSTROT 1996).

The more precise real time DGPS service (HEPS) is partly realised by employing 2 m-band transmitters, for the transmission of the real time correction data in the RTCM 2.1 format, covering areas with a radius of 15 to 50 km. In order to increase the precision, processes are under development to derive the correction data from more than 1 station (from a network of some stations).

BKG makes use of 24 h data from 20 stations covering all states of Germany (GREF) and derives on a daily basis station coordinates in order to maintain an active national reference frame, to monitor station movements and to derive meteorological parameters (GENDT et al. 1995), (Weber et al.1997).

## Phase center variations

Emphasis has been placed on the investigations of antenna phase center variations. Different antenna types have been compared through collocation measurements and models have been derived for the determination of the phase center dependent on the satellite elevation and azimuth.

The investigations have been carried out by the Deutsches Geodätisches Forschungsinstitut (DGFI), the Institut für Erdmessung of the University Hannover, the Geodätisches Institut of the University Bonn and has been supported through collocation measurements at the Fundamental Station Wettzell by the BKG (KANIUTH et al. 1998, KANIUTH et al. 1995, ROTTACHER et al. 1995).

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# Positioning for global and long range applications

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## Introduction

In the period from 1995 to 1999 German institutions have contributed to positioning for global applications employing VLBI, SLR and GPS techniques. Continuous operations have been carried out at the Fundamentalstation Wettzell by the operation of the 20m Radio telescope, and the Wettzell Laser Ranging System (WLRS) in EOP-, crustal dynamic- and reference frame projects. In addition the Transportable Integrated Geodetic Observatory(TIGO), which is foreseen to be placed on a site in the Southern hemisphere has been established. Observations in O'Higgins (Antarctica) have been continued with the VLBI-Antenna, the GPS and PRARE System

Several GPS campaigns have been conducted with a strong support from German institutions for the establishment of continental wide reference frames for Europe (EUREF and EUVN) and for the realization of a regional reference frame in South America (SIRGAS and CASA).

Sea level Projects such as SELF has been performed and several geokinematic campaigns have been carried out as GEODYSSEA, CERGOP, AEGAIS, WHAT A CAT, SCAR/GAP. Finally some local activities have been performed. The readjustment of the leveling network UELN has been performed including new links to Central and East European countries (UELN95).

### VLBI and SLR

The Bundesamt für Kartographie und Geodäsie (BKG) in cooperation with the Forschungseinrichtung Satellitengeodäsie (FESG) (Technische Universität München) on behalf of the Forschungsgruppe Satellitengeodäsie (FGS) have carried out continuously VLBI-observations with the 20m Radio telescope and SLR-observations with the Wettzell Laser ranging System (WLRS) in order to support the International Earth Rotation Service (IERS) for the determination of the Earth orientation parameter, and the realization of the ITRF and ICRF. At the Station O'Higgins in the Antarctica, periodically VLBI, continuously GPS and PRARE observations have been performed. BKG, the Deutsche Geodätische Forschungsinstitut (DGFI) and the Geodätische Institut/University Bonn (GIUB) have contributed to the IERS annual solutions by VLBI, and SLR data analysis. The TIGO has been set up and first experiments have been successfully conducted. The tests and experiments have been carried out at the Fundamentalstation Wettzell in collocation with the VLBI-, SLR- and GPS-systems. (DREWES 1998, HAAS et al. 1997, HAAS et al. 1998, KANIUTH et al 1998, PETROV et al. 1998, SCHMITZ-HÜBSCH 1997, SCHUH et al. 1997, DICK, RIEPL et al. 1997, RIEPL, SCHLÜTER et al. 1996, SCHLÜTER et al. 1997, SCHLÜTER et al. 1998, SCHLÜTER et al. 1998, Thorandt et al. 1996, Thorandt et al. 1997, SCHLÜTER et al. 1995, SCHLÜTER et al. 1996, SEEGER et al. 1995, MEINIG et al. 1995, REINHOLD et al. 1995)

The permanent GPS-activities are described in the chapter “Permanent GPS Networks and Realtime Positioning” by W. SCHLÜTER and K. PAHLER.

### EUREF and EUVN

The EUREF activities have been started in the year 1989, with the objective to realize a uniform reference frame all over Europe for scientific and practical applications. Within the period from 1995 to 1999 regional activities have been conducted in order to extend the network and to densify EUREF. For the campaigns in Bulgaria, Island, Luxembourg and Romania, which have been observed in the previous years, final results have been evaluated and published (ALTINER et al. 1996, ENGELHARDT et al. 1995, ENGELHARDT et al. 1995, FRANKE et al. 1996, MARJANOVIC et al. 1995, NEUMEIER et al. 1996, , NEUMEIER et al. 1996, FRANKE et al. 1995/96, NEUMEIER et al. 1995/96, NEUMEIER et al. 1995/96). In 1995, 1996 and in 1998 sub-campaigns for EUREF have been carried out in Croatia, Slovenia, Bulgaria, Malta, Albania, FYROM, and in Yugoslavia. The results have been published in (SEEGER et al. 1995, SEEGER 1995, SEEGER et al. 1996, ALTINER et al. 1995/96, ALTINER et al. 1997, FRANKE et al. 1997, SEEGER 1995/96, SEEGER et al. 1996, ALTINER et al. 1997, ALTINER et al. 1997, ALTINER, AMBERG et al. 1997, SEEGER et al. 1997, SEEGER et al. 1997).

In the year 1996 in the frame of EUREF a GPS campaign has been proposed to place emphasis to the height component. It resulted in the establishment of the European Vertical GPS Reference Network (EUVN). EUVN combines EUREF sites, nodal points of the levelling networks such as UELN and UPLN and tide gauges. The campaign, consisting of 195 sites, has been observed in 1997. The final objective is to provide for all EUREF sites the GPS-coordinates and heights with respect to the European levelling networks. Final coordinates derived by GPS have been published. For most of the sites the levelling information is collected and available. It is expected to complete EUVN in the next year. (ADAM et al. 1997, IHDE et al. 1996, ENGELHARDT et al. 1998, FRANKE et al. 1998, IHDE et al. 1997, SCHLÜTER et al. 1998, INEICHEN et al. 1998, LUTHARDT et al. 1998, SCHLÜTER et al. 1998)

### UELN95

The reajustment of the UELN (Unified European Levelling network) has been performed by the BKG. In order to include new countries in the UELN some new links have been observed and included. The adjustment has been published as UELN95/98. (LANG et al. 1995, AUGATH et al. 1996, LANG et al. 1995, LANG et al. 1996, LANG et al. 1997, LANG et al. 1997)

### SIRGAS

A major contribution for the establishment of the regional reference frame for South America, the "Sistema de Referencia Geocéntrico para América del Sur" (SIRGAS) has been made by the DGFI (Deutsches Geodätisches Forschungsinstitut). DGFI strongly supported the observations and performed the data reduction and analysis. (DREWES 1997, DREWES et al. 1997, DREWES 1998, DREWES et al. 1998, KANIUTH 1998, KANIUTH et al. 1998, MOIRANO et al. 1997, MOIRANO et al. 1998, SEEMÜLLER et al. 1997)

### Self -Project

With support of the European Union the SELF I and SELF II project has been carried out. For the investigation of sea level variations in the area of the Mediterranean Sea, GPS-technique was employed to determine recent crustal movements at tide gauge stations. At more than 28 tide gauges and at several reference sites repeated GPS observations have been carried out in the period from 1993 to 1998. At some selected sites BKG and the ETH Zürich supported the project with water vapour radiometers in order to provide additional data to improve the determination of the refraction correction. (ZERBINI et al. 1996, ZERBINI et al. 1997)

### Geodynamical projects

Repeated GPS campaigns for the determination of crustal movements and geokinematical investigations have been supported in the Asian Area (GEODYSSEA), in the Central European Area (CERGOP) in the Aegean area (AEGAIS) in the Westhelenic and Calabrian Arc (WHAT A CAT), in regional areas of Turkey and Croatia, in Central and South America(CASA) and in the Antarctica (SCAR/GAP),. The geodynamic projects are reported in the chapter "Recent Crustal Movements and deformations" by W. Augath. (KANIUTH et al. 1998, BECKER et al. 1995, BECKER et al. 1995, MARJANOVIC et al. 1995, REINHART et al. 1996, AKSOY et al. 1997, AKSOY et al. 1996, ALTINER 1996, ALTINER et al. 1997, ALTINER et al. 1997, ENGELHARDT et al. 1997, ALMEDA et al. 1997, ALTINER et al. 1997, BECKER et al. 1997, BOONPHAKDEE et al. 1997, BECKER et al. 1997, BECKER et al. 1997, BECKER et al. 1997, DIETRICH et al. 1997, DIETRICH 1996, ENGELHARDT et al. 1996, ENGELHARDT et al. 1996, ENGELHARDT et al. 1996, IHDE et al. 1996)

### GLONASS

A first geodetic global campaign employing GLONASS has been carried out in order to compare GLONASS with GPS and to investigate the difference in scale (ZARRAOA et al. 1996).

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# Positioning for close range and engineering applications

B. WITTE
with contributions by M. BÄUMKER, H.-P. FITZEN and E. GROTEN

## Close range applications of GPS

Due to improved GPS technologies and methods new application fields for GPS in the close range up to 2 km have been developed and described in the past four years. For the static GPS method new algorithms have been used and applied to survey the official network. A report and praxis test are given by LINDSTROT et al. (1997). COORS et al. (1998) have been examined the capability of different GPS receivers in respect to short baselines. AUGATH (1997, 1998) and WANNINGER (1997) have been focussed on the use of permanent reference stations (SAPOS) for GPS measurements for official surveyings, engineering surveyings and for real time applications.

The integration of GPS measurements into existing networks is since the introduction of GPS a permanent field of research and is of great importance for surveying practice. (GRÜNDIG (1997); NIEMEIER (1996); SCHNÄDELBACH (1995)).

Another field of application gets more important: kinematic GPS measurements, especially in real time. This subject have been evaluated by KUHN et al. (1998), BILAJBEGOVIC and VIERUS (1998). The examinations are partly overdriven by the rapid development of new algorithms and receiver types (PENZKOFER (1999)). BINNENBRUCK et al. (1998) are using the GPS-RTK method in conjunction with a SAPOS reference station for official surveyings in the land register.

The kinematic and OTF-method is frequently used for engineering projects. KITTLAUS and REICHENBACH (1996) have been reported over satellite-supported opencast mine surveying and mass calculations. Monitoring of disposal sites with GPS-RTK is the subject of NIEMEIER and HOMANN (1996) and HOMANN and BRAMMER (1997). In HEIN and RIEDL (1995) new possibilities and future capabilities to monitor deformations have been forecasted.

Highest accuracies are achieved for monitoring purposes using the static method with long observation time. SPARLA (1995) uses sessions of several hours. Thus the results are calculated like classical measurements only for discrete epochs. New solutions based on permanent measurements are highlighted by NIEMEIER (1998) but lasting no longer than several days. A new high accurate and reliable GPS measurement method has been developed for single frequency receivers by BÄUMKER and FITZEN (1996).The method is continuously applied in real time over several years and delivers standard deviations for the horizontal position of ± 1 mm or better. Experiences and results gathered during the monitoring of a dam over several years are given in FITZEN and SCHRAVEN (1998).

There exists a wide variety of applications in surveying engineering and other technical fields. Only some examples for instance a positioning system for mobile mapping (AUSSEMS (1995, 1999); BENNING, AUSSEMS (1998)), an application for road traffic guidance (MÖHLENBRINK, MEZGER (1996), examples for deformation analysis (SALER (1995); FRITZENSMEIER (1996)) or for road surveying in forests (OVERBERG et al. (1995); SCHMITT, RAWEL (1997); KUHN (1997)) etc. can be given here.

Another important field of application is the integration of GPS determined ellipsoidal heights into a standard height reference system. About this topic there exist many publications so that only a part of them can be mentioned here (DINTER (1997); DINTER et al. (1996); ILLNER, JÄGER (1995); ZHONG (1997, 1999)).

The combination of GPS measurements with terrestrial observations is becoming an interesting tool in surveying practice . In order to improve the efficiency of control point, engineering and cadastral surveying work special models are developed to solve the problems connected with this task. GRÜNDIG (1995); ASCHOFF et al. (1995); NIEMEIER (1995); LANG (1996); (MARKUZE and WELSCH (1996); WERTHEIMER (1996); ERNST et al. (1999). The compensation of influences caused by deflections of the vertical and refraction is achieved by a method developed by ZHONG et al. (1997). Another interesting application is the determination of the movement vector and the strain rate of a glacier (LANG and WELSCH (1997).

The accuracy of GPS measurements is generally limited by multipath and errors of the GPS antennas. New methods and fundamental principles to calibrate the antenna phase center variations (PCV) have been published by CAMPBELL et al. (1996) WÜBBENA et al.(1996) and KANIUTH et al. (1998).

## Engineering applications

Besides the application of GPS in engineering surveying, nowadays a more or less classical field of research, there exist many other new developments. Only a few of them will be mentioned here. An overview concerning the trends and future perspectives in engineering surveying are given by SCHLEMMER (1996). A new hybrid 3-dimensional coordinate measuring system for close range applications was developed by HOVENBITZER (1998). The integration of surveying and guidance systems for roadworks machines is explained by DIETZ et al. (1996). Besides that automatic measuring systems for the determination of building deformations using special devices like e. g. inclinometers and digital levels were successfully employed by SCHAUERTE and AUSTERSCHMIDT (1996). In order to get a better understanding of such solutions it may be necessary to read SCHLEMMERs book (1996) about basics of sensors and sensor-systems in connection to surveying.

Much effort is put in a research project in order to take the influence of vertical and horizontal refraction into account using digital sensors e. g. CCD-cameras (SCHAUERTE, DEUSSEN (1997), CASOTT et al. (1998)).

## Inertial techniques

As far as geodetic research is concerned, centers of primary interest for surveying and airborne gravimetry are the Bavarian Academy, FAF University at Munich, and GFZ in Potsdam; interest in non-linear dynamics and airborne surveying dominates at Stuttgart University and navigation and terrestrial surveying at Darmstadt University.

The „Sonderforschungsbereich 228“ was for many years one of the centers of the application of INS-technology in Germany (LINKWITZ and HANGLEITER, 1997). In succession of it, collaboration with „Electropribor“ in St. Petersburg was continued by the SFB-group in Darmstadt. The results were published in several papers (DMITRIEV et al., 1997; TRAISER et al., 1998). Positioning based on GPS + INS as well as attitude control by INS was afterwards studied, in view of engineering applications, by the same group. Results were summarized in (GROTEN and SEITZ, 1998; HEINZE, 1996; SÖHNE, 1996). All these investigations were based on a Lasernav II Honeywell laser ring platform which proved to be good to an accuracy of several centimeters in INS + GPS-application when updating was possible within a few seconds of time. With updating of one second intervals (using DGPS) even airplane surveys showed such accuracy. More complex hybrid systems, using CCD-camera plus a vertical laser installed in a VW-van-system together with INS-GPS were tested for a variety of surveying application based on kinematic techniques. In this way, INS proved to well supplement „OTF-technology“ in GPS kinematic applications (GROTEN et al., 1998; MATHES, 1998; MATHES and 1998).

At GIS of Stuttgart University (J.H. DAMBECK, 1998) did a compact, but rigorous derivation of the system of (non-linear) inertial navigation differential equations, in several combinations of spatial coordinates and parametrizations of the group of rotation matrices, and a detailed investigation of their properties and the principal limits of the procedure of inertial navigation. The modelling includes the linearization, the system augmentation by general stochastic sensor error models, the discretization and a compilation of useful Kalman filters and smoothers. Different sources of instability of an unaided inertial navigation system model are identified and their local invariance with respect to regular state transformations is proven. Errors in the vertical components of the correction of gravity in the (vertical component of the) acceleration vector sensed by the accelerometer triad and hence a vertical mis-acceleration of the means of locomotion on which the inertial navigation system is mounted. Without external observations nobody can distinguish between systematic sensor errors and a variation shortcoming which the observability analysis shows to exist is, that the rotation angle around the acceleration vector sensed by the accelerometer triad in a stationary navigation period is not observable, in case position and velocity observations, e.g. by usage of single antenna DGPS. This includes the well known lack of observability of the azimuth during „fine alignment“ in static mode. Furthermore the invariance of the observability property with respect to bounded state transformations is proven and it is shown, that in static mode the initial orientation and sensor biases are not simultaneously observable. The observability of sensor drifts is given. A system simulation to analyse the influence of different error sources upon the states and the processing of real data from a Litton LTN-90-100 including an extensive sensor data analysis and an autonomeous initial orientation determination show the usage of the presented models and their stability. For further contributions see (LINKWITZ and HANGLEITER, 1997).

Prof. CASPARY from the FAF University at Munich reports:

The inertial navigation system is combined with other sensors ( DGPS, odometer, barometer) in the kinematic survey system KiSS. The system serves to support the determination of the position, in particular in the case of GPS outages and for the determination of the attitude angles for the exterior orientation for the photogrammetric evaluation of digital stereo images.

Systems of different accuracy which are based on mechanical gyroscopes, on fiber-optical ones or laser gyroscopes are used.

These systems are examined with regard to the following aspects:

- of the sensors and the system calibration
- capturing of the raw data of the sensors
- navigation equation
- hardware-integration with other sensors
- software-integration with other measurements

Development of a 'low-cost' system with reduced sensor configuration and reduced accuracy for navigation and position finding.

G. HEIN and B. EISSFELLER (Inst. of Geod. and Navigation of FAF-University, Munich) report about the following research projects:

*A. Integration of GPS with a SAGEM Sigma 30 Strapdown INS for Airborne Vector Gravimetry*

The Institute of Geodesy and Navigation of the University FAF Munich currently undertakes research activities for building up an airborne gravimetry system, using measurements from a highly stable and accurate SAGEM Sigma 30 Strapdown INS and precise kinematic results from GPS carrier phase and phase rate data. The goal is to determine the full gravity disturbance vector from the moving aircraft with high accuracy.

The gravity disturbance vector is directly affected by INS and GPS measurement noise and resulting accuracy is determined by the error characteristics of both measurements. The resolution of the gravity spectrum depends on the signal to noise ratio in different frequency bands. Problems that are addressed are filter design for a band-limited gravity spectrum and specific aircraft dynamics. To reduce the critical errors of the INS sensors and GPS receivers, spectral filtering techniques and Kalman filtering are applied, which are the standard estimation techniques in vector gravimetry. One key element currently under research in this project is the design of a shaping filter for modeling the anomalous gravity field by means of spectral factorization. Since the gravity field functionals deflections of the vertical and gravity disturbance are also present in the linear dynamic error equations of the INS, attempts will be put on augmenting the navigational and sensor error equations by a linear gravity field shaping filter in the time domain. The approach for the stochastic treatment of the anomalous gravity field will be the use of Markov type gravity models, including not only a distance dependence, but also a height dependence (EISSFELLER 1996).

The hardware configuration of the airborne gravimetry system is separated into a rover station (mobile vehicle, aircraft) and a reference station for generating the GPS corrections. The rover station consists of the SAGEM INS, a Personal Computer, devices for automatic reading and data logging, power supply, GPS receiver and antenna, telemetry and antenna, as well as interface/synchronization cards and accessories. The hardware of the GPS reference station is comprised of a PC with power supply, GPS receiver, antenna and a telemetry module with antenna. The extension of the system (rover station) with respect to the connection of additional sensors (e.g. barometric height sensor etc.) will be taken into account. In a first step, the system will be tested with road vehicle tests along specific traverses in the inertial testnet "Werdenfelser Land" in the South of Bavaria. Then, performance demonstrations of the INS/GPS gravimetry system by aircraft flights are planned for the near future.

*B. Integration of DGPS with a SAGEM SIGMA30 Strapdown INS for railway surveying*

The Institute for Geodesy and Navigation of the University FAF Munich currently joins a Research Project of the EU to investigate the process of derailment. An essential element in derailment studies is the knowledge of the track condition. Therefore a precise and reproducible method is needed for exact railway survey. A key element is to find a precise reference point on a rover from where measurements of the track geometry can be done.

The institute undertakes research activities for developing a navigation platform to determine this reference point, using measurements from a highly stable and precise strapdown INS (SIGMA30, SAGEM, France) and precise results from differential GPS carrier phase and phase rate data. The measurements of both sensors are combined in a Kalman filter, which is the standard estimation technique in INS/GPS integration.

The hardware of the navigation system consists of a rover station, which will be mounted on a train and a stationary reference station for generating the GPS corrections. The rover station is built-up by the SAGEM SIGMA30 Strapdown INS, GPS antenna and receiver, a Personal Computer, an Uninterruptable Power Supply (UPS) and devices for synchronization of all measurements units. For the reference station, a GPS antenna and receiver and a mobile Personal Computer is used. Data processing will be made offline to get the advantage of data smoothing.

*C. Integration of a low-cost INS with a GPS receiver*

The Institute for Geodesy and Navigation of the University FAF Munich currently undertakes research activities for building-up a tightly coupled “low-cost navigator”. The availability of low cost inertial sensors results in an increasing interest in integrated GPS/INS systems. The idea of integrating inertial sensors with GPS is not new and has been done previously, but with higher accuracy of low cost inertial sensors and the availability of GNSS receiver chips, a tightly coupled integration of GNSS pseudo range measurements and high rate inertial data using a closed-loop Kalman Filter becomes feasible. The observations are pseudo-ranges to the GNSS satellites and position and velocity of the inertial sensor, i.e. Systron Donner Motion Pak, whereas the system state is described by errors of the sensors (offset, drift, scale factor error) and errors of navigational values (errors in attitude, velocity and position). The basic problem when using low – cost inertial sensors is the approach of stochastic modeling, because the sensor errors show sudden changes in the time domain.

W. MÖHLENBRINK (IAGB, Univ. Stuttgart) reports:

*Multi-Sensor-Data Fusion for Car Navigation*

During the last 2 years a gyro-supported positioning algorithm for car navigation was developed. Sensor models for wheel sensors, magnetic field sensors, and rigid body gyroscopes were combined with map matching algorithms based on curvature patterns of digital road maps especially for urban areas with restricted GPS/DGPS availability. These autonomous positioning techniques are of high practical relevance. Positioning accuracies of 1 m and better were achieved.

R. RUMMEL (IAPG, TU Munich) reports:

In a theoretical study a general inertial measurement unit operated in strapdown mode is investigated, see (DOROBANTU, 1998). Departing from the nonlinear electro-mechanical system with noise the error behaviour is studied for operation in closed loop and open loop. Effects such as sensor non-linearities, resonances, asymmetries, temperature behaviour, drifts are studied and respective transfer functions derived. An extended Kalman filter for a complete system simulation has been formulated in SIMULINK – MATLAB language.

A field experiment has been carried out for a GPS – aided low-cost strapdown mechanised IMU for vehicle navigation in the city of Munich. Both pseudorange and precise carrier phase DGPS has been tested. The navigation algorithm has been formulated for a linearised state variable system in 3-D, using a linear Kalman filter and then implemented in 2-D. The algorithm is available in MATLAB. Theory and test results are described in DOROBANTU and ZEBHAUSER (1999).

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# SECTION II

# ADVANCED SPACE TECHNOLOGY

# Advanced space technology

## – Overview and highlights –

R. RUMMEL

Section II of IAG is concerned with new Space techniques for geodesy and geodynamics. Its objectives are to anticipate and promote their implementation into geodetic/ geodynamic work and, in general, support and coordinate the optimal use of Space technology for the benefit of geodesy. The chapter here comprises, after this overview, a section 'Space Observation Instrumentation and Satellite Systems', a section 'Space borne atmospheric monitoring' and a section 'satellite orbit modeling'.

A large segment of geodetic research in Germany deals with Space geodesy. There are the orbit modeling activities at the ESA center ESOC in Darmstadt, the Earth oriented Space research at the GeoForschungsZentrum Potsdam (GFZ), the work related to the Fundamental Station Wettzell, in particular that of the Research Group for Space Geodesy (FGS), and the research at a number of university institutes. A large part of this work is carried out in international programs or in the context of the IAG services. Some of the research is coordinated on a national level, such as the studies on Earth rotation or coordinated research in support of the CHAMP mission, both supported by the German Research Foundation (DFG).

Geodetic Space techniques provide us with a global terrestrial reference frame and with its connection to the celestial frame. These two elements are the backbone of all further geodetic activity, whether applied or scientific. It is amazing that this global task is carried out with such excellence on a voluntary basis. It involves the coordinating effort of a large number of stations, computer centers, sub-centers, coordinators etc. Germany plays an important role in it. For geodetic practice, the terrestrial reference frame is the top level of a hierarchy of the continental, national and regional reference frames, nowadays more and more implemented as active permanent services for a wide range of users. In science it is the terrestrial reference frame to which all activities related to geo-kinematics, Earth rotation and gravity field are tied to.

After so many years of Space geodesy one could expect research in this field gradually slowing down. The contrary is true. With the first transportable fundamental station TIGO of the Bundesamt für Kartographie und Geodäsie (BKG) the weakness in the realization of a global reference frame due to the uneven distribution of the observatories over the globe can be diminished in the future. The PRARE system shows its capability as primary tracking system on ESA's ERS-2 satellite. Satellite laser ranging has been improved both in terms of precision and reliability. Never had there been more laser targets in orbit, ranging from low orbiters such as GFZ-1 via the LAGEOS satellites to a few GPS satellites equipped with laser retro reflectors. VLBI, very efficient already now, will be further improved by the MARK-IV technology, new correlators and in the future probably by real time capabilities. First tests with VLBI phase measurements over short baselines are very promising and may increase base line accuracies. Interferometric SAR is a new addition to the arsenal of geodetic Space techniques. It is applied to topographic mapping of land and ice surfaces and, in a differential mode, for deformation analysis on land and ice. Altimetric data analysis has reached a level of maturity and precision such that it can be employed with great success for ocean and climate research, e.g. for the improvement of tidal models, the study of the southern oscillation and for sea level research.

Several institutions in Germany are participating in one way or the other in the activities of the International GPS Service (IGS), such as ESOC, GFZ, BKG, the German Geodetic Research Institute (DGFI) and the Bayerische Kommission für die Internationale Erdmessung (BEK). More and more activities have recently been added to the successful work of the IGS, in addition the classical ones, the maintenance of a network of permanent stations that constitutes a global geodynamic observatory and the provision of precise ephemerides of all of the GPS satellites. Orbits are provided almost in real time now, precise orbit determination of the GLONASS satellites is currently tested and the use of GPS for atmospheric sounding makes great progress.

With the availability of this enormous wealth of data also gravity modeling has progressed. However, in comparison with global deformation studies and Earth rotation the accuracy, completeness and spatial resolution of gravity field determination is lacking behind. This situation will change very soon and, I suppose, in a very comprehensive manner. Three gravity research missions are in preparation. The German CHAMP satellite is close to completion and will be launched in 2000, lead by GFZ. It will be the first satellite to apply the combination of low orbit, high-low satellite to satellite tracking to the GPS satellites (SST-hl) and micro-accelerometry. The US-German mission GRACE is also approved and will fly in 2001. It will apply high precision tracking between two low orbiting satellites. Finally, the ESA explorer mission GOCE, currently studied in phase A, will use gravity gradiometry for the first time in Space. The objectives of the three missions are complementary. Their successful realization is a great challenge for the participating industry and laboratories. At the same time they offer a wonderful opportunity for geodesy and for Earth sciences as a whole with applications in solid Earth sciences, oceanography, hydrography, sea level and climate research.

In conclusion, one can look back to four very successful years in Space geodesy and for sure the coming four years will continue to be exciting too.

# Space observation instrumentation and satellite systems

CH. REIGBER

Various government agencies, research centers and university institutes in Germany have been actively involved in the design, development and operation of space geodetic observing systems and low Earth orbiting missions. This section summarizes the major activities in this field during the reporting period. The use of data from these instruments or satellites is described in other parts of this report.

## Microwave tracking systems

Permanent ground tracking stations for the GPS and GLONASS systems were established for system control tasks, support of user services and the development of new ground- and space-based applications. By operating a permanent GLONASS receiver since 1995, the DLR-DFD Remote Sensing Ground Station Neustrelitz is maintaining a GLONASS Updated Information Service (GUIS) (ZARRAOA et al. 1997, 1998), which provides a near real time evaluation of GLONASS data quality. Continuous operation of a GLONASS and GPS receiver at the Wettzell tracking site of the Forschungsgruppe Satellitengeodäsie (FGS) provides besides other results the link of the GLONASS time with the UTC (GPS) time scale (HABRICH 1998). The Bundesamt für Kartographie und Geodäsie (BKG) has developed and is operating in cooperation with the Deutsche Telekom AG a differential GPS data service through low frequency (DITTRICH & KÜHMSTEDT 1995, DIEROFF et al. 1996). This service, called ALF (Accurate positioning by Low Frequency), is presently being used by about 1000 customers primarily from agriculture and car-navigation (DITTRICH et al. 1997). In support of the International GPS Service (IGS), the GeoForschungs-Zentrum Potsdam (GFZ) is operating 7 permanent GPS receivers on the South American and Eurasian plates (GALAS 1996, 1997). A similar number of receivers is provided by the BKG (BECKER 1997, WEBER 1997) for the IGS. In support of the radio-occultation experiment of the CHAMP and GRACE missions for deriving vertical soundings of key parameters of the atmosphere, GFZ is establishing in cooperation with NASA's Jet Propulsion Laboratory (JPL) a global network of 15 high rate Turbo Rogue Benchmark receivers (REIGBER et al. 1999). The locations of these sites are selected in such a way that project requirements for an operationally robust network, for short data latency and global distribution of profiles as well as requirements of the IGS can be fulfilled.

Besides their contribution to global monitoring networks, primarily BKG and GFZ have supported permanent regional GPS networks for various applications. Whereas GFZ is focussing its permanent GPS station operation towards South America and Asia in order to support regional geodynamic investigations (REINKING et al. 1995, KLOTZ et al. 1995, ANGERMANN et al. 1997, REIGBER et al. 1999), BKG's permanent station operations are concentrated on the German territory and additionally some stations in the larger European area (WEBER et al. 1996, 1997, 1998). The main purposes of these permanent networks are monitoring of the national and European reference systems, their link to the international terrestrial reference frame and their use for differential GPS navigation applications (REINHART et al. 1997, SEEGER et al. 1997). As reported in the following chapter, both institutions have started recently to use the dense regional network data for studying the tropospheric water vapour distribution over Germany and adjacent areas.

The Hochschule der Bundeswehr München (HSBW) and the GFZ were or are involved in the tests, verification and operation of GPS flight receivers on Low Earth Orbiting (LEO) missions. BALBACH et al. 1998 reported on the successful operation of a Motorola flight receiver on the Max Planck Institute's Equator-S spacecraft, launched in December 1997 into a very elliptic near equatorial orbit with an apogee distance of 64,000 km, far beyond the altitude of the satellites of the GPS configuration. From 1996 to 1998 a single frequency Motorola receiver was operated on the Russian space station MIR as one element of the navigation package for the German MOMS remote sensing experiment. Routinely provided orbit ephemeris results by GFZ over this period (FÖCKERSPERGER et al. 1997) were successfully used to orient the images of the MOMS camera. Presently a NASA/JPL manufactured high performance TRSR-Black Jack space receiver is being integrated and tested in the CHAMP spacecraft (REIGBER et al. 1999). After successful launch into orbit, this receiver will perform three different tasks: (1) precision orbit determination, (2) atmosphere and ionosphere sounding, (3) ocean/ice reflection measurements.

The Precise Range and Range Rate Equipment PRARE (FLECHTNER et al. 1997) was launched after a successful test flight on a METEOR3 mission (BEDRICH & FLECHTNER 1996) in 1995 on ESA's ERS-2 spacecraft into a 770 km altitude orbit as primary tracking system. PRARE is a two-way dual frequency range and range rate system which has demonstrated during its now almost 4 years operation time (1) a very effective data gathering from the global network stations through the onboard generation and storage of tracking and corrective data (REIGBER et al. 1997), (2) a very efficient preprocessing and dissemination of preprocessed tracking data with only a few hours latency (FLECHTNER et al. 1997), (3) a high quality of tracking data i.e. 2 to 3 cm for the ranges and 0.1 to 0.15 mm/sec for the range rates (BEDRICH 1999) and

(4) rapid determination of orbits from PRARE data for the generation of rapid altimetry products and determination of precision orbits for determining station positions, the motion of stations and for the improvement of GRIM-gravity models (MASSMANN et al. 1997, ENNINGHORST et al. 1998). Time transfer experiments and the use of the dual frequency measurements for the total electron monitoring have demonstrated the wide applicability of PRARE measurements (BEDRICH & HAHN 1997). The PRARE space module A has been functioning without problems onboard ERS-2 since 1995. With the redundant PRARE module B aboard not been used yet, it is very likely that PRARE will continue to provide high precision tracking data until the end of life of ERS-2.

## Satellite and lunar laser ranging

The institutions involved in laser ranging in Germany are the BKG and GFZ. The GeoForschungsZentrum Potsdam is operating a better than 2 cm Nd:Yag system on the Telegrafenberg, dedicated to the tracking of low orbiting spacecrafts such as GFZ-1 (KÖNIG et al. 1996), the calibration of the PRARE system onboard ERS-2 (REIGBER et al. 1995) and support of altimetry and gravity field missions (MASSMANN 1995, 1996). Being in operation since 1989, this 3rd generation station is going to be replaced by a new one in 1999.

The BKG is operating at the FGS site Wettzell the high precision WLRS system, capable of ranging to 800-40,000 km distant artificial satellites and to the moon (SCHREIBER et al. 1997). Various modifications and improvements were introduced in the reporting period to resolve a station calibration problem and to achieve the sub-cm precision for the single shot ranges (RIEPL 1997, 1998). BKG's mobile SLR system MTLRS-1 was continued to be used in the WEGENER-MEDLAS project in 1995. After a development period in 1996 it was used stationary for collocation experiments at the Wettzell site and is now phased out of routine operation after the SLR-module of the Transportable Integrated Geodetic Observatory TIGO started to deliver ranging data in collocation with the WLRS in 1998 (HASE et al. 1998). The TIGO system is designed as a compact transportable fundamental station composed of a base module providing power, computer resources, environmental and geophysical corrective data, and an SLR- and a VLBI-module. It is planned to commence operation on the southern hemisphere in 2000.

## Very long baseline interferometry

The German involvement in VLBI is continuing to be high owing to the activities of the Research Group on Satellite Geodesy (FGS) and the BKG. Since its first tests in 1983, the 20m radio telescope at Wettzell has been participating almost 16 years now with high intensity and reliability in a large number of geodetic VLBI experiments, which are now being merged into the CORE programme (Continuous Observation of Rotation of Earth) (HASE et al. 1998). These programmes which were coordinated by the IAG/COSPAR Commission on the International Coordination of Space Techniques for Geodesy and Geodynamics (CSTG) and will soon be managed by the International VLBI Service (IVS) aim at the determination of Earth orientation parameters with highest precision and temporal resolution and the provision of the link between the celestial and terrestrial reference frames. The Wettzell 20m system, which has been upgraded to the Mark-IV-standard, new recording and computer devices, is one of the key stations in this context (HASE 1997).

The DLR-SAR receiving station at the Chilean base General O'Higgins in Antarctica was continuously used by BKG for VLBI observations in a campaign style form. With this 9m-dish, experiments were scheduled in the framework of the IRIS-, CORE- and O'HIGGINS networks for contributing to Earth orientation investigations, reference frame tasks and geodynamic studies in Antarctica (ENGELHART et al. 1997; THORANDT et al. 1997). The future for VLBI operations with the O'Higgins system is not yet decided after BKG's reorganisation.

The TIGO VLBI-module consisting of a 6m–off axis antenna, an X/S band receiving system and a Mark IV data recording system started first fringe tests on the baselines Wettzell-Effelsberg/Onsala in November 1997. After necessary modifications, the system started generating observations in the NEOS-A and EUROPE networks in 1998 and is planned to commence operation on the Southern hemisphere within the TIGO system in 2000 (HASE et al. 1998).

## SAR interferometry

Synthetic Apertur Radar interferometry is a technique that allows the extraction of topographic information by means of SAR. It is based on the generation of an interferogram between two complex SAR images of the area acquired from two spatially separated radar antennas. The two images can either be acquired by two antennas on the same moving platform (single-pass interferometry) or by using one antenna in repeated passes over the same area at different times (repeat-pass interferometry) (VACHON et al. 1995). A repeat-pass geometry can also be generated by using two identical antennas on two different satellites following each other in almost the same orbit. This so-called tandem scenario can presently be used with ESA's remote sensing satellites when the active microwave system of both satellites ERS-1 and ERS-2 is switched on. When using two SAR observations of the same area at different times and assuming a change in topography in the time between two observations, the interferometric phase of the interferogram, formed from the two images contains in addition to the topographic information the information about the displacement. This so-called differential SAR interferometry (D-INSAR) technique was applied by various geodetic groups in Germany for studying tectonic deformations (XIA et al.1997, REIGBER et al. 1997), small motions in mining areas (TIMMEN & XIA 1996, 1997), changes in the shape of volcanoes, landslides and ice dynamics (DIETRICH et al. 1999). Data reception for most of these applications was performed with the mobile 4m dish SAR receiving station, purchased jointly by DLR and GFZ and operated since 1997 in Cordoba/Argentina, Bishkek/Kyrghyzstan and Kitab/Uzbekistan by a DLR/GFZ crew (REIGBER et al. 1999). This system has INSAR and D-INSAR processing capability on site and can therefore be used for monitoring tasks. The second receiving antenna is the 12m dish at the O'Higgins/Antarctica site, which is operated by DLR in a campaign style and is used for ice topography, mass balance and ice flow studies (JONAS et al. 1996, DIETRICH et al. 1998).

## New gravity field missions

In the reporting period three new gravity missions fully or partly funded from national space programme resources entered the exploitation or realization phase. These missions are the passive small laser retro reflector satellite GFZ-1 (KÖNIG et al. 1996), the high-low satellite-to-satellite tracking mission CHAMP (REIGBER et al. 1996) and the US/German low-low satellite to satellite tracking mission GRACE (TAPLEY & REIGBER 1999). A fourth mission with strong German impact on the system design was approved by the European Space Agency for a phase A study; it is the gravity gradiometer mission GOCE (MÜLLER et al. 1997).

In April 1995 the 20 kg retro reflector equipped cannonball satellite GFZ-1 was separated from the Russian MIR station into a 51.6° inclined orbit at 400 km altitude (KÖNIG & REIGBER 1996). The satellite was designed by the company Kayser-Threde (SCHULTE et al. 1995) and manufactured by the Russian firm RNIIKP. GFZ-1, now decayed to an altitude of 280 km, has been observed by the global laser tracking network over the last four years. The data from this very low satellite have been integrated into various gravity field solutions (KÖNIG at al. 1996). End of life of GFZ-1 is predicted for June 1999.

CHAMP is an active small satellite, the basic scientific goals and scientific payload instruments of which were defined by GFZ scientists in 1995 (REIGBER et al. 1996). CHAMP, mainly funded by DLR, entered phase C/D in January 1997, and was fully assembled and integrated in April 1999 (REIGBER et al. 1999). The different test phases commence in May 1999 and launch of the spacecraft from the Russian launch site Plesetzk is planned for January 2000. CHAMP will be launched into a 87 degree inclined 450 km orbit and over the 5 years lifetime the payload instruments will allow to measure the Earth's gravity and magnetic fields and their temporal variability and will sound the neutral atmosphere and ionosphere through the refractivity of the radio signals (REIGBER et al. 1998). The mission science payload consists of a 16 channel Turbo Rogue space receiver (provided by NASA/JPL), a STAR accelerometer (provided by CNES/ONERA), an ion drift meter (provided by the USAF/AFRL) and Overhauser- and Fluxgate-Magnetometers, star imagers and a laser retro reflector set provided by the project.

The Gravity Recovery And Climate Experiment mission GRACE was selected in NASA's Earth System Sciences programme (ESSP) in 1997 for a launch in June 2001 (TAPLEY & REIGBER 1999). The realization of this US/German mission is based on a 4:1 funding of the project. The mission consists of a satellite pair separated by 200-300 km and cross-linked by a K-band ultra precise ranging system. Non-gravitational forces accelerations are separated through measurements of ONERA's SuperStar accelerometer. The on-board GPS receiver provides high-low tracking data, provides time synchronization and extracts K/KA-band phase data. In addition it is used for sounding the atmosphere and ionosphere.

GRACE has entered the phase C/D in January 1999 and is planned to be launched into a 89.5 degrees and 450 km altitude orbit in June 2001 from the Russian launch site Plesetzk.

German scientists are heavily involved in the definition and design of ESA's Gravity and Ocean Circulation Experiment (GOCE) mission. GOCE is a spaceborne gravity gradiometer mission belonging to the ESA programme Earth Explorer missions (ESA 1996). The mission has just passed phase A and activities were in the reporting period focussing on mission and system design investigations (SNEEUW et al. 1996, MÜLLER et al. 1998). Simulation studies show that the three forthcoming gravity missions CHAMP, GRACE and GOCE are quite complementary what concerns the gravity recovery part of the missions (MÜLLER et al. 1997, BALMINO et al. 1998).

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# Spaceborne atmospheric monitoring

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GNS (Global Navigation Systems), as there are GPS and GLONASS, primarily serve positioning and timing purposes. In recent years the GPS networks are developing support of meteorological applications including climate and climate change studies and operational weather forecasting.

By evaluating the refraction of GNS signals moving through the Earth's atmosphere, the atmosphere can be sounded from ground and space. Operational determination of zenith path delays for ground observations of nowadays 150 sites became a standard product of the IGS (International GPS Service) starting in 1997. The individual estimates from all the IGS Analysis Centers are combined at the GeoForschungsZentrum Potsdam (GFZ) to generate an official IGS product. The derivation of water vapour by simultaneous measurements of surface pressure data is available for about 20 out of those 150 stations (GENDT, 1998).

The horizontal resolution of the monitoring network can be increased by regional densifications like in Germany where rather dense networks of permanently operating GPS stations are under construction. The Land Surveying Agencies in the 16 states of Germany are establishing the SAPOS network of more than 250 sites, of which 160 are already in place. The final network will have a spacing of about 50 km all over Germany. This high quality infrastructure could be used for the meteorological community with a relatively small additional effort. In cooperation with the DWD ("Deutscher Wetterdienst" i.e. German Weather Service) and as an initial step into the European Union COST 716 program activities, the GFZ has started a test campaign for near real-time water vapour determination in 1998. Ten GPS receivers are installed at the synoptic DWD sites. This experiment will provide a good insight into near real-time water vapour estimations and will deliver a basic data set for test of software and technology. First results show that also in near real-time an accuracy of 1-2 mm PWV (Precipitable Water Vapour) can be achieved.

The Bundesamt für Kartographie und Geodäsie routinely analyses the data of the EUREF and GREF densification networks in Europe. The data of about 40 stations is processed each day and tropospheric zenith delay parameters are estimated. The use of these data in cooperation with the DWD is studied in view of the generation of precipitable water vapour estimates for meteorological applications (see BECKER et al. 1998a, BECKER et al. 1998b, BECKER et al. 1999, WEBER et al. 1998).

The application of spaceborne GPS to atmospheric limb sounding was successfully demonstrated by the proof-of-concept mission GPS/MET launched in April 1995. Today the radio occultation method promises a similar revolution in science as was the case for GPS precise point positioning and other geo-related desirables.

It should be noted that a combination of ground-based GPS atmospheric sounding and the occultation technique is very interesting for the meteorological community. The added value of both approaches to monitor the atmosphere is related to the fact that the ground-based method may provide a good horizontal resolution whereas the latter method leads to a high vertical resolution. Combining both methods will therefore compensate the shortcomings of each single technique.

A variety of small satellite missions has adopted atmospheric sounding experiments in addition to their main science objectives. In space are OERSTED and SUNSAT since February 1999, CHAMP is scheduled for a launch end of 1999 (REIGBER et al., 1998), SAC-C probably in 1999, GRACE in 2001 (TAPLEY, REIGBER, 1998). A dedicated space array of 8 satellites named COSMIC is scheduled for launch in 2002. ESA (European Space Agency) is planning to fly their GRAS (GNSS Receiver for Atmospheric Sounding) on-board the Metop satellites with a first launch in 2003 aiming at an operational space constellation in the time frame 2012 to 2017. All these missions will generate a data set eagerly awaited for by the meteorological community.

The German CHAMP project started in 1995 with an intensive mission design update including also all elements of the radio occultation experiment planned to be carried out on-board the CHAMP satellite (REIGBER et al., 1996). Since the GPS radio limb sounding technique is rather young, considerable work is focussed on the further development of this technique itself. In brief, the outcome of the radio occultation experiment on-board CHAMP shall be an operational system which provides a number of deliverables according to the international state of the art in this field. Typical products are: vertical profiles of bending angle, refractivity, temperature, pressure, humidity in the troposphere and stratosphere and electron density and TEC (total electron content) in the ionosphere. Up to 250 profiles on global scale are expected per day and satellite.

Since a precise determination of the bending angle requires accurate frequency shift and range measurements, clock instabilities of on-board GPS receivers have to be compensated. This is realized by installing a fiducial GPS ground station network which enables the compensation of all clock errors by computing double differences. In preparing the CHAMP and GRACE missions, GFZ and JPL (Jet

Propulsion Laboratory) are just installing such a GPS network consisting of about 16 GPS sites globally distributed. The stations work autonomously and self-controlling to fulfill high operational requirements (e.g. REIGBER et al., 1998). The network serves also to support precise orbit computations on a high operational level. Other important data sources are the global IGS network and SLR (Satellite Laser Ranging) measurements. To ensure accurate data products the bending angle has to be measured with an accuracy of 1 µrad. This requires an accuracy of a few centimeters for radial position and of less than 1 mm/s in tangential velocities for the involved satellites.

To transform vertical profiles of the refractive angle into vertical refractivity profiles, the Abel transformation has been tested and implemented (e.g. HOCKE, 1997, JAKOWSKI et al., 1998c). Furthermore, a routine retrieval of water vapour profiles of the lower troposphere is under development, in particular to check applications in numerical weather prediction. To enhance the height resolution to the sub-kilometer level or to start with the retrieval close to the earth surface, diffraction and multipath effects shall be reduced by appropriate correction methods (PAVELYEV, HOCKE, 1998).

Since the ionospheric refraction above about 30 km exceeds the neutral gas contribution, various correction algorithms have been tested by simulation runs or are under development (FICKERT et al., 1997). Due to the electromagnetic interaction of radio waves with the ionospheric plasma, radio occultation measurements on-board CHAMP provide an additional capability to get more information about the ionized region surrounding the earth. Utilizing the dispersive nature of the ionospheric plasma, the dual frequency GPS signals allow the estimation of the ray path integrated electron density or TEC. The main advantage of radio limb sounding measurements for sensing the ionosphere is the entire profiling of the electron density from the bottom at about 60 km through the F2 layer up to orbit heights. The corresponding algorithms have been tested or are under development (e.g. JAKOWSKI et al., 1997) Using globally distributed ground based GPS measurements as provided by IGS, TEC maps can be constructed as e.g. for the European region (JAKOWSKI, 1996, JAKOWSKI et al., 1998e).

The monitoring of the ionosphere in form of TEC by GPS was also triggered by IGS activities (FELTENS et al., 1996). In future the tomographic combination of ground-based and spaceborne radio occultation data can describe 3D electron density distribution. In situ measurements of space weather from CHAMP on-board data (LÜHR et al., 1998) will synergistically add a complement to these studies.

Since May 1995 the German PRARE microwave tracking system is operational on ERS-2. It provides TEC data based on two-frequency measurements or DRVID data (Differenced Range Versus Integrated Doppler) with an accuracy of about 2 TEC units (FLECHTNER et al., 1998).

In order to correct SLR measurements for the refractive index of the atmosphere this contribution can be modelled from meteorological parameters, obtained in the vicinity of an SLR tracking station on the ground. These models which were tuned with the help of radio sondes data are quite precise, however it is believed, that they do not account properly for horizontal gradients and untypical meteorological situations. Dual colour laser ranging and lidar measurements offer the opportunity to probe the atmosphere along the line of sight by remote sensing. A number of experiments such as dual colour laser ranging, using avalanche photo diodes and a streak camera for the fundamental (infrared) and second harmonic (green) wavelength of a Nd:YAG-laser have been carried out in the past few years to exploit this approach for improved range corrections. From these measurements it seemed that the influence of water vapour for the optical refractive index is not fully accounted for in the range correction models. Raman shifted backscatter lidar measurements were also attempted to determine the tropospheric water vapour content. The obtained profiles are not yet precise enough to be used for an improvement on the atmospheric correction models. See RIEPL et al. 1995, 1997, and SCHREIBER et al. 1995, 1997, and RIEPL 1998.

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# Satellite orbit modelling

J. M. DOW

A large number of publications in the period 1995-99 covered topics relating to satellite orbit modelling. In the field of earth observation, precise orbit modelling and orbit control of ERS-1 and -2 and TOPEX/Poseidon allowed significant advances to be made, notably in use of altimetry and SAR interferometry data. Improvements in modelling the orbits of the GPS spacecraft led to exploitation of a wide range of new applications. Modelling for upcoming missions for gravity field improvement also had high priority.

On the theoretical side, YOU (1995) discussed the perturbed motion of a satellite in terms of minimal geodesic flows on Maupertuis manifolds, according to the Maupertuis variational principle of least action, and in terms of KS elements. Analytical dynamic orbit improvement was used by CUI and LELGEMANN (1995, 1999) for the evaluation of geodetic satellite data. A systematic development of this approach was provided by CUI (1997). Gravitational forces were treated using canonical transformations (with Hill variables) and Lie series. Non-linear coupling and resonance effects were included, whereby strong resonances were handled through Taylor series along with the non-gravitational forces, by means of Encke linearisation.

Arfa-Kaboodvand developed a software package for accurate and flexible computation of the perturbations acting on a satellite (ARFA-KABOODVAND 1997), relying on orbital equations formulated using Hill variables, and non-gravitational force modelling based on Monte-Carlo ray tracing techniques. Average effects of incident flux on the satellite are determined by tracing the path of a representative sample of individual rays or particles, taking into account spacecraft physical and geometric properties.

Precise orbit modelling of the ERS satellites was an important topic of research: excellent accuracy could be achieved, permitting improved processing for satellite altimetry and more reliable models of mean sea surface and sea surface variations. For the first time accurate and timely models for the temporal development of the El Nino Southern Oscillation and its counterpart La Nina could be derived from satellite altimeter data. Contributions to ERS orbit solutions are discussed by MASSMANN et al. (1997a, 1997b) and by ZANDBERGEN (1997a, 1997b) and DOW (1999).

Significant advances were made in precise modelling of the GPS orbits, in the context of the activities of the International GPS Service IGS. Improved accuracy could be combined with reduction in the delays for availability of rapid and final products, and a daily orbit prediction product (combining inputs from several analysis centres) was introduced, providing real-time GPS orbits with typical accuracy of 50 cm or better. Initiatives in a number of new directions were undertaken (GENDT and DICK, 1996), and the IGS analysis centre activities continued to consolidate and expand (DOW, KOUBA and SPRINGER, 1998). One important advance was the initiation of an International GLONASS Experiment (IGEX) involving a global network of GLONASS and GPS/GLONASS receivers. Several Analysis Centres (Bern, BKG, ESOC, GFZ) succeeded in obtaining very accurate (a few dm) GLONASS orbits on a daily basis since October 1998, which is leading to resolution of reference frame and radiation pressure modelling issues for the GLONASS constellation.

Satellite to satellite tracking (SST) from GPS spacecraft to TOPEX/Poseidon was analysed from the point of view of precise orbit determination (POD) and gravity field modelling by SCHWINTZER et al. (1995). As test data undifferenced GPS pseudorange and phase measurements by TOPEX/Poseidon were used. In a two step adjustment the Topex orbit was first computed, then the measurement data from one 10 day repeat cycle were included in the GRIM4 normal equations. A detailed study of GPS SST for orbit and gravity field improvement and an extensive simulation of gravity field recovery using these methods was performed by KANG (1998), which suggested excellent possibilities for gravity field improvement through the CHAMP mission. Other analyses concentrating on POD for TOPEX were made by CASOTTO et al. (1995), where agreement at the level of 2-3 cm radially with SLR and DORIS solutions was demonstrated. KANG et al. (1997) described some tests involving processing of GPS SST data collected through the GPS/MET mission, in which the utility of estimating empirical accelerations was emphasised. One of the key instruments aboard the CHAMP satellite will be the three-axis STAR accelerometer, which will measure the non-gravitational accelerations on the satellite, and allow separation of the gravitational signal. A simulation carried out by SCHWINTZER, KANG and PEROSANZ (1998) demonstrated the feasibility of adequately estimating the accelerometer calibration biases from a few days of data.

The use of high precision GPS orbit and clock products for determination of the absolute and relative motion of pairs of space vehicles carrying single-frequency GPS receivers was demonstrated in the processing of data from three brief flight experiments involving the Space Shuttle (MARTIN-MUR et al., 1998).

The GFZ-1 spacecraft was released into a 400 km orbit from the Mir space station in April 1995 (KÖNIG et al. 1996a). Laser ranging data over 42 days incorporated into the GRIM4-S gravity model produced notable changes in the gravitational spectrum around orders 15, 31 and 46 (KÖNIG et al. 1996b, 1997).

In the framework of preparatory activities for a European Global Navigation Satellite System, HEIN, SU and EISSFELLER (1997) studied orbit determination scenarios for a possible constellation of inclined geosynchronous satellites in three planes, supplemented by three geostationary satellites.

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# SECTION III

# DETERMINATION OF THE GRAVITY FIELD

# Determination of the gravity field

## – Overview and highlights –

G. BOEDECKER

One key idea in natural sciences which is particularly apparent in this context is the idea of a **model**. In the context of gravity field related problems it means the mapping of the infinitely dimensional real (gravity) world space – with often a large number of observations – to a finite dimensional space spanned by a **set of rules** and a **set of data**. The set of rules in this context are primarily algorithms based on physical and mathematical developments. The inherent simplification can be considered a hypothesis or an approximation. If the model is dominated by data, the model can also be named '**representation**'.

*Example*: A global gravity field model is defined by an algorithm, e.g. spherical harmonic expansion, and a set of data, coefficients given by numerical values. This could also be named a 'representation' of the gravity field. This label is even more justified e.g. in case of a collection of mean topographic heights collected in a clearly defined manner and referred to some reference surface.

The terrestrial gravity field can be represented by i. (scalar) gravity (or gravitational) potential or by ii. its first order (vector) gravity gradient or iii. its second order (tensor) field. Observables are available on either level; resulting models are also possible on either level, depending on the application. Obviously, deriving potential (i.) from gravity (ii.) requires the solution of a differential equation including the proper boundary value problem.

**Observables:** Satellite altimetry essentially scans the vertical position of an equipotential surface of the gravity field i.e. level i. Most gravity field observation methods, however, use level ii., namely the observations of accelerations (=specific force) inferred from the geometric position of a proof mass: terrestrial absolute meters as also satellite orbit observation rely on tracking the trajectory of a freely falling proof mass (dynamic method), spring gravimeters including superconducting a spring-proofmass system with position determination (static method). Gradiometry works on level iii. and requires the observation of the (relative) positions of two proof masses, be it within one box for terrestrial application or onboard a satellite, be it in the form of two satellites (SST). Besides the above, additional types of observables affecting gravity are available, e.g. topographic data.

**Progress in gravimetric research** requires the advancement of the immediate observation methods and methods to link observations to model space; for heuristically structuring the contributions, we apply the following bins:

1. Direct gravity observation techniques and instrumentation for terrestrial and airborne observations
2. Focus on physical geodesy methods and satellite observations methods
3. Focus on mathematical methods
4. Projects with emphasis on numerical gravity model results
5. The link between the gravity field models and the real Earth

The about 250 **publications** collected for this German report to IAG Section III, were authored by more than 100 scientists based at some 15 German institutions, many of the authors are on temporary positions, the majority are geodesists. Most of the papers were presented to meetings, some were prepared for PhD theses and journal articles.

This overview survey of contributions prepared in Germany by intention does not follow the structure of the subsequent detailed reports in order to provide a different view angle and hence to support additional insights; for the same reason the respective research groups are mentioned instead of authors – except for a few highlights. References are found in the subsequent detailed reports.

As to subject 1, **direct gravity observation techniques and instrumentation for terrestrial and airborne observations**, research on *absolute gravimetry* at BKG Frankfurt and IfE Hannover confirmed after repeated observations and intercomparisons that repeatability over a number of years with modern instrumentation is better than 30 $nms^{-2}$ and the stability of good stations at the same order of magnitude. The study of *relative spring gravimeters* at BKG, IfE, TPG Dresden dealt with data logging, calibration, environmental effects and electronic feedback and achieved an accuracy of less or more than the above number, very much depending on the application. Time series recordings with *superconducting gravimeter*s were advanced by IAGP Jena and BKG, which acquired a newly developed dual-sphere instrument that enables significant improvements. *Environmental effects* including earth tides, air pressure, temperature, ground water, on gravity observations were studied by IAGP, BKG, GFZ Potsdam, IPG Darmstadt. *Gravity reference networks* are at the verge of observational techniques to data collection.; they serve e.g. for the transfer of relative observations to absolute gravity, calibration, gravity changes monitoring etc. IfE was engaged in establishing base networks in Dubai, South America, Germany, China with many absolute observations; BKG was busy in Germany, Netherlands, Scandinavia, several countries in eastern Central Europe, Turkey, Greece, Italy, Spain, Antarctica. *Gravity reference networks* dedicated to geodynamics investigations were established in Indonesia by IAGP and IPG and on Philippines and in Colombia by IAGP, in Greece by TPG. *Kinematic gravimetry* such as airborne gravimetry has many advantages over conventional terrestrial observations such as increased efficiency and coverage of inaccessible areas. GFZ reported the results of a joint European campaign with rms of 20mms$^{-2}$ and a spatial resolution of 6-7 km; these figures were obtained using a conventional LaCoste&Romberg airborne gravimeter with gyro stabilized platform; GFZ also sponsored an instrumental SG development for airborne application. BEK München is trying to employ inertial grade accelerometers in a strapdown airborne gravimetry system for ease of operation and increased spatial resolution. IfEN Neubiberg dealt with the total error budget which shows the critical role of GPS high precision kinematic positioning. BGR Hannover tested car borne gravimetry.

> Summarizing the activities of bin 1, absolute gravimetry passed the threshold from an advanced developing stage to production, where repeatability figures now should approach real accuracies and bad surprises should be extremely unlikely; future developments may lead to miniaturization and enhanced fieldworthyness. Relative spring gravimeters are production instruments since decades, nevertheless improvements are still possible. The changing role of gravity reference networks as driven by the developments of absolute and relative field gravimeters has been reviewed by TORGE (1998). Superconducting gravimeters for high precision time series recordings still offer very interesting potential for further development, as shown by the dual sphere device (RICHTER & WARBURTON 1998), which enables better identification of tares and use for vertical gradiometry; a development of SGs for field observations remains a future target. The complete control of environmental effects on gravimetry still is the challenge for high precision observations. As to airborne gravimetry, TIMMEN (et al., 1998) demonstrated competence to keep up with airborne gravimetry at international standards; BOEDECKER's (1997) approach has promising potential for high resolution airborne gravimetry, but requires quite some work. In any case, high precision kinematic positioning is a prerequisite.

As to bin 2, **focus on physical geodesy methods and satellite observation methods**, *boundary value problems* and *differential geometry of the gravity field* are discussed by GIS Stuttgart, *upward/downward continuation* was studied by GIS, GIK Karlsruhe and IfEN Neubiberg. One physical model for the Earth's gravity field is a *point mass model* as employed by GIK and IGG Berlin.

(Quasi-) *Geoid computations* from various combination solutions are pursued from GPS/levelling + gravity by BKG Leipzig, IfE Hannover, from global model + local gravity by IPG Darmstadt, GIK, D-PAF. Numerical solutions are presented for many areas including small areas like Berlin by IGG to Antarctica by TPG. Quality checks of geoid computations are possible because of redundant regional information from gravity, levelling, GPS, see e.g. IfE Hannover, GIK Karlsruhe

Studies aiming at methods for *computing gravity field quantities from topographic masses* have been carried out by IGG Berlin, GIS.

The *theory of height systems* is discussed in IAPG München with application to Indonesia, by IfE Hannover, GIS, IGG. *Satellite missions* such as GFZ's future low flying CHAMP with GPS tracking and the refinement to care for surface forces from high atmosphere by onboard accelerometers were studied by GFZ Potsdam, in a broader view also the GOCE- and GRACE missions are discussed by IGG Berlin and IAPG München, who point out the improvement for global gravity field models.

> Problems of bin 2 seem to be a classical stronghold of German geodesists since many decades. It seems that boundary value problems and gravity field differential geometry never end under new aspects like a deformable Earth etc, cf. Grafarend and coauthors (1995-98). Height systems unification obviously pose a new task in the light of cm GPS heighting capability. Also the old problem of forward modelling like terrain reduction showed interesting new algorithms like the volume to line integral approach of PETROVIC (1996).
>
> The handling of own satellites for gravity field observations such as GFZ1 and CHAMP (REIGBER and coauthors 1996-99) certainly is a breakthrough in international competition, albeit. New satellite missions will approach the physical limit for the spatial resolution of gravity field observations from space, which is of the order of around 50 km (except altimetry).

As to bin 3, **focus on mathematical methods**, *wavelet methods* with the advantage over spherical harmonics of space localization were given strong attention by GeoM Kaiserslautern. *Spectral properties* of the gravity field were studied by IAPG München which also developed an efficient global spherical 2D FFT method. A *gravity field shaping filter* for Kalman filtering was developed by BEK München. *Efficient algorithm* development was pushed in GIK Karlsruhe. High resolution geoid computations under *limited computer resources* are attacked at BKG Berlin.

> It is breathtaking how wavelets pour into the gravity field with the inherent space localization capability and making aware of the referring deficiency of spherical harmonics (Freeden and coworkers, continuously). Even if the current enthusiasm will cool down like after the introduction of geodetic prediction/collocation some 20 years ago, it will remain a valuable new tool in geoscientists toolbox. Advances in efficient algorithms are developed by LEHMANN (1995-99) and STRAKHOV/SCHÄFER (1995-99).

In bin 4, **projects with emphasis on numerical gravity model results**, of course have to rely on methods developed in bin 2 and bin 3. As to the data, tracking of satellites with different orbit characteristics and hence corresponding contributions to specific spherical harmonics is the backbone of global long wavelength information. G*lobal satellite-only model*s such as GRIM4 with extension to 34 satellites including the first GFZ-satellite observations, resulting in GRIM4-S4, were computed by GFZ Potsdam and D-PAF Oberpfaffenhofen. GFZ Potsdam also started with the follow-up model GRIM5 which is to include PRARE and ERS-2 data to provide a solution complete to degree and order 100 with some additional terms, also in preparation of the future CHAMP satellite mission of GFZ. *Global combined solutions* enable higher spatial resolution by including satellite altimetry derived gravity anomalies over the oceans as computed e.g. by D-PAF Oberpfaffenhofen from observations by ERS-1, GEOSAT and TOPEX satellites, and terrestrial gravity anomalies, usually in the intermediate form of mean block (e.g. 30'x30', 5'x5') gravity anomalies, often made available from data collections like BGI and NIMA. These mixed data sets require special attention to homogeneity and weighting. Several strategies were developed particularly by D-PAF and resulted in models complete up to degree and order 360; an ultra-high degree model up to degree and order 1800 was presented by GIK Karlsruhe.

*Regional models* such as the EGG97, computed by IfE Hannover required data collection in the framework of European high resolution geoid computation project for many years and now 2.7 million gravity data and 700 million terrain data are incorporated in the data base.

> It has to be noted that global as also extended regional high resolution gravity field model computations require an integrating view on tedious data collection, algorithm efficiency, data combination/weighting. DENKER and colleagues (1995-99) at IfE has demonstrated that extended regional quasigeoid computations such as the EGG97 are good to few cm and therefore match GPS heighting accuracy. The benefit of the of GRIM geoid models is a global accuracy of the order of 70 cm, for the long wavelengths much better. GRUBER and colleagues (1995-99) have contributed heavily to model refinement, algorithm efficiency and data combination problems solutions for global gravity model solutions.

In bin 5, **gravity field representation** and **the link to the real Earth**, we find the immediate gravity as such: NLfB Hannover presents Bouguer gravity maps of various parts of Germany including interpretations, also employing observations of the 'Geophysikalische Reichsaufnahme' transformed to IGSN71 reference.

The link works in two directions: Our immediate knowledge of the Earth in terms of topographic and density models can be exploited by *forward modelling algorithm*s such as developed in IAPG München, GIS Stuttgart or IGG Berlin. See also bin 2.

In the *inverse problem*, gravity field signals may be interpreted as isostatic phenomena, crustal density structures, sea surface topography, see GFZ Potsdam, IfE Hannover, IPG Darmstadt. Numerous regional geological studies based on gravity were carried out in Germany, see IAGP Jena and NLfB Hannover, also combined with magnetic, seismic, borehole surveys, in order to infer on the shape of a disturbing body.

> It is obvious that in the area of interpretation, i.e. linking the gravity field and the material world, also to circumvent the potential pitfalls of the inverse problem, combination with non-gravity data is necessary which also results in a cooperation with non-geodetic geoscientists. PLAUMAN (1995-98) completed a comprehensive gravity surveys in Germany, JENTZSCH and co-authors (1995-99) linked gravity to local geology and processes in time.

**Acronyms of institutes used:**

BEK (München): Bayerische Kommission für die Internationale Erdmessung bei der Bayerischen Akademie der Wissenschaften

BGR (Hannover): Bundesanstalt für Geowissenschaften und Rohstoffe and Geowissenschaftliche Gemeinschafts-aufgaben

BKG (Frankfurt): Bundesamt für Kartographie und Geodäsie, Frankfurt (earlier IfAG), also Berlin and Leipzig

GeoM (Kaiserslautern): Fachbereich Mathematik / Geomathematik, Universität Kaiserslautern

GFZ (Potsdam): GeoForschungsZentrum Potsdam

D-PAF (Oberpfaffenhofen): GFZ – Deutsche Processing and Archiving Facilities (branch of GFZ)

GIK (Karlsruhe): Geodätisches Institut, Universität Karlsruhe (TH)

GIS (Stuttgart): Geodätisches Institut, Universtität Stuttgart

IAGP (Jena): Institut für Angewandte Geophysik, Universität Jena

IAPG (München): Institut für Astronomische und Physikalische Geodäsie, Technische Universität München

IfE (Hannover): Institut für Erdmessung, Universität Hannover

IfF (Braunschweig): Institut für Flugführung, Universität Braunschweig

IfEN (Neubiberg): Institut für Erdmessung und Navigation, Universität der Bundeswehr Neubiberg (near München)

IGG (Berlin): Institut für Geodäsie und Geoinformationstechnik / Fachgebiet Mathematische, Aatronomische und Physikalische Geodäsie, Technische Universität Berlin

IPG (Darmstadt): Institut für Physikalische Geodäsie, Technische Universität Darmstadt

ITG (Bonn): Institut für Theoretische Geodäsie, Universität Bonn

NLfB (Hannover): Niedersächsisches Landesamt für Bodenforschung

TPG (Dresden): Institut für Planetare Geodäsie, Fachgebiet Theoretische und Physikalische Geodäsie, Universität Dresden

# Absolute and relative gravimetry

M. BECKER

## Abstract

Progress in gravimetry is led by instrumental improvements of absolute gravimeters and in superconducting gravimeters which enhance the accuracy and the resolution in the monitoring of variations in gravity. A major role played the monitoring of environmental effects on both the instruments and the gravity signal. National gravity networks as precise reference were improved and networks for geodynamical studies and for environmental hazard prevention were set up in several projects within and outside of Germany.

## 1. Introduction

The determination of gravity changes is still a challenging task. The progress in instrumentation is slow but noticeable, especially with absolute and superconducting gravimeters. In order to keep track with the forthcoming new space techniques for gravity field determination, the terrestrial gravimetric techniques are needed to complement and verify the results obtained by satellites. The availability of a network of high resolution continuously monitoring instruments and its support by the combination with absolute measurements will be crucial to this task. These applications, as well as geodynamic and hazard prevention gravity networks still rely to a great extent on conventional spring gravimeters. Therefore the continuos improvement of these instruments and the techniques for modeling environmental and instrumental and calibration effects is necessary and has to be stimulated. In the sequel the main works in Germany are reviewed. Only the major references are cited and it is tried to give a complete list of relevant publications in the references.

## 2. Absolute gravimeters

The quality of the JILAG-3 absolute gravimeter of IFE (Institut für Erdmessung, University of Hannover) was continuously controlled by repeated observations on the reference stations Clausthal (hard bedrock, repeatability over more than 10 years < 0,04 mms-2) and Hannover (sediments, repeatability < 0,08 mms-2). JILAG-3 also participated at the fourth and fifth international comparison campaign of absolute gravimeters at BIPM in Sevres in 1994 (MARSON et al. 1995) and 1997. The results deviated from the mean epoch values by + 0,03 mms-2 and + 0,05 mms-2

Since 1993 IfAG/BKG (Institut für Angewandte Geodäsie, renamed 1997 in Bundesamt für Kartographie und Geodäsie, Frankfurt a.M.) operates the absolute gravimeter AXIS FG5-101. The instrument was used in national and international projects for the determination of reference systems and the survey of geodynamical networks. To monitor the instrumental performance and long term stability the station Bad Homburg was selected as primary reference station and instrument home base. About 70 repeat measurements over 6 years with a Sigma of ± 30 nms-2 proved the stability of absolute gravimeter and station. To verify the relation to the international gravity standard which is established by the pool of absolute gravimeters worldwide, FG5-101 participated in the Fourth and Fifth international comparison campaigns of absolute gravimeters at the BIPM in Sevres in 1994 (MARSON et al. 1995) and 1997. A special intercomparison in Boulder, 1995 (KLOPPING et al. 1997) confirmed the determination of the so-called discriminator effect detected in Sevres 1994. After an instrument upgrade FG5-101 participated in a comparison campaign in Boulder, 1997. Reference measurements at the German Geodetic Fundamental Station Wettzell are carried out 3 to 4 times per year.

## 3. Spring- and superconducting gravimeters

Initiated by BKG a Dual-Sphere superconducting gravimeter was developed at GWR (RICHTER, WARBURTON 1998). The two sensors in this instrument enable to detect instrument-induced steps and to assess the instrumental drift function. This improves the observation of the gravity signal and the geophysical interpretation. The instrument was delivered to BKG end of 1997; after adaptation to the European electrical standards the instrument operated in a test phase in Frankfurt and since December 1998 continuously observes in Wettzell. First results show the significant improvement of the superconducting gravimeter system. The IAGP (Institute of Applied Geophysics, University of Jena) acquired a new superconducting gravimeter for its Geodynamical Observatory Moxa. Other instruments installed are ET-18, quartz- and laser strainmeters, tiltmeters. Other studies with superconducting gravimeters were made in cooperation with China (JENTZSCH, 1996, KRONER et. al, 1995).

IFE continued to operate several relative gravimeters (LaCoste Romberg-LCR-model G and D, with SRW electronic feedback systems, LCR with ZLS Land Update, SCINTREX) for establishing fundamental and geodynamical gravity networks, and performing dedicated research. Calibration of the relative gravimeters was controlled at the Hannover calibration system, in order to keep the periodic calibration errors at the order of 0,01 mms-2. The SCINTREX CG3-M gravimeter was investigated at the calibration systems Hannover and Karlsruhe, and the high quality of this instrument was confirmed (REHREN, 1997).

At the ITG (Institut für Theoretische Geodäsie, Universität Bonn) instrumental investigations on LCR gravimeters with respect to humidity and calibration were undertaken (BONATZ, 1996a,b) and a new system for monitoring tectonic processes was presented (BONATZ, 1996c). At IPG (Institut für Physikalische Geodäsie, Techn. Universität Darmstadt) the automated data-logging system for field gravimetry "Feldgrav was enhanced. IPG, IFE as well as BKG participated in the fifth intercomparison of absolute gravimeters which also included a relative campaign for calibration and instrumental investigations on spring gravimeters (BECKER, 1999).

## 4. Gravity networks and calibration systems

Fundamental papers on the changing role of gravity reference networks and on the use of gravimetry for monitoring recent crustal movements have been published by TORGE (1998a,b) and TORGE (1995).

At the establishment of national networks IFE was engaged at the Emirate of Dubai (1994: 3 absolute and several relative stations, AL ZAFFIN et al. 1997) and in the Netherlands (1991, 1993, 1997: 5 absolute stations with 3 repetitions between 1991 and 1993) in cooperation with the responsible state survey agencies. The IFE absolute gravity program 1988 – 1991 in South America established stations in Venezuela, Brazil, Uruguay, and Argentina, which were used for improving the national networks and for supporting geodynamical nets along the Central and the Venezuelan Andes (TORGE et al. 1995). The national gravity network of Uruguay, where IFE established 3 absolute stations at the end of the 1980s was readjusted, including the calculation of a gravimeter calibration line (TIMMEN et al. 1997, SUBIZA et al. 1998). At the resurvey and extension of the German Gravity Base Network DSGN94, IFE participated by occupying 5 stations with JILAG-3. By comparing the results with the values obtained by the FG5-101 absolute gravimeter of IfAG/BKG a bias of 0,08 mms-2 was found, which was confirmed at the comparisons at Sevres. The residual discrepancies are within a few 0,01 ms-2 (RICHTER et al. 1998a,b).

In the Western Yunnan Earthquake Prediction Experiment Area (WYEPEA), in cooperation with the Institute of Seismology/SSB Wuhan, another absolute/relative gravimetry campaign was carried out in 1995 by IfE. Altogether 12 absolute stations (6 in WYEPEA) have been established at the campaigns 1990/1992/1995; including stations in Beijing, Wuhan and Kunming, with relative ties between them for control and for connecting local networks and GPS stations (LAI et al. 1996). The results of the surveys (JILAG-3 precision < 0,01 mms-2, accuracy < 0,05 mms-2 or better) are published in TORGE et al. (1999), a discussion of local changes due to surface and ground water level variations (up to 0,1 mms-2) is given in JIA et al. (1998).

Around the German coast lines 11 absolute gravity stations were established by JILAG-3 between 1994 and 1997. The stations are close to selected type gauges and shall serve by later repetitions as an independent control of vertical movements at those sites. The reliability of the control system has been monitored by control measurements at the inland stations Hannover, Clausthal and Potsdam, and by relative ties between the absolute stations. Seismic and tilt control was carried out at each station, for quality assessment and post processing. The precision of the gravity values at these coastal stations is < 0,01 – 0,02 mms-2, the accuracy is estimated by < 0,05 mms-2 (REHREN et al. 1994).

IFE also continued investigations of gravimetric earth tides. Within the absolute gravity project along the German coast lines gravimetric earth tide stations were established at Aurich and Helgoland (German Bay) and at Rostock close to the Baltic Sea. The results for Aurich and Rostock agreed with the global earth tide model, while the Helgoland island station showed slight differences. Cooperating with Prof. WENZEL, Karlsruhe a model of world wide synthetic gravity tidal parameters was developed (TIMMEN and WENZEL 1995).

The data evaluation for the German gravity reference network, DSGN94 have been completed. The results are exclusively based upon absolute gravity measurements with the FG5-101 gravimeter. Measurements with relative gravimeters were made as an independent control. The overall accuracy is ± 0,05 $\mu ms^{-2}$, comparisons with the previous network in the western part of Germany show a significant offset but no significant change in scale.

The AdV (Arbeitsgemeinschaft der Vermessungsverwaltungen der Länder) working group "Base Networks" asked BKG to analyze the data of the DHSN96. In the connecting range between the new federal states and the DHSN82 in former federal states a significant offset was detected. The activities and the status of the gravity works in the AdV in Germany are described in WEBER (1998) and BOLJEN (1999).

BKG conducted a number of international campaigns with FG5-101. Repeat measurements on 6 stations in Sweden and Norway have been carried out in 1993, 1995 and 1998 as a cooperation with the Norwegian Mapping Authorities and NOAA to monitor the Fennoscandian post-glacial uplift. The measurements in Ny-Alesund, 1998 establish a reference for ice balance and uplift investigations. After an initiative of the US Defense Mapping Agency BKG and the University Trieste in 1995/96 jointly carried out absolute gravity measurements on stations in Poland (5 stations), Czech Republic (2 stations), Latvia (1 station), Slovenia (6 stations), Hungary (2 stations) and Croatia (4 stations) to densify and connect the gravity systems in Central Europe.

In a cooperation of BKG and the Turkish General Command of Mapping a network of 14 new absolute gravity stations have been determined in Turkey, 1996 with 4 stations on Satellite Laser Ranging platforms of the WEGENER project, 5 tide gauge stations, 3 national gravity network stations and 1 station of the Turkish gravity calibration baseline (WILMES et al.1997).

On request of the Meetkundige Dienst 3 absolute gravity stations have been determined with FG5-101 in the Netherlands, 1996.

In the framework of the SELF II project (Sea Level Fluctuation Experiment) absolute gravity BKG has carried out measurements in Spain (3 repeat measurements and 3 new stations) and Greece (2 stations). Five repeat measurements in Medicina (Italy) in conjunction with continuous registration of the superconducting gravimeter SG-23 of BKG served to monitor significant gravity changes at the station. (SCHWAHN et al, 1999, ZERBINI et. al, 1996).

In 1997 absolute gravity measurements in Iceland served to establish a first order reference network with 7 stations along the coast line and in the interior part of the island. The works were carried out jointly by the Iceland Geodetic Survey and BKG.

In an Antarctic expedition on the research vessel “Polarstern” of the Alfred-Wegener Institute, November 1997 – January 1998, the FG5-101 gravimeter was brought to the Antarctic VLBI station O’Higgins of BKG / DLR on the Antarctic peninsular. Successful absolute gravity measurements could be carried out in O’Higgins and Jubani/Dallmann at King-George-Island.

The EU-financed project UNIGRACE (Unification of Gravity Systems in Central and Eastern Europe) comprises partner institutions from 12 states in Central and Eastern Europe. The project started in 1998 and is coordinated by BKG (REINHART et al.1998a, b). In the first field campaign absolute gravity measurements have been carried out with FG5-101 on 7 stations in Poland, Romania and Germany.

As an update of the 1993 Unified European Gravity Network (UEGN), emerged from activities of the Subcommission Western Europe of the IGC, it is planned to do a readjustment including more countries and more recent observations, also in cooperation with the UNIGRACE project. Gravity data of a few countries have already been made available.

## 5. Environmental effects

The influence of the air-pressure on gravity and gravity observations was studied in detail by IAGP (KRONER, 1997 and further references). They were supported by a research project on “Coherence-structures of gravity variations and meteorological events in the nm$^{-2}$ level”.

Further studies on air pressure effects on spring and superconducting gravimeters were undertaken at the GFZ (Geo ForschungsZentrum Potsdam) by Dittfeldt (pers. Comm.).

Within the activities in the SELF II project BKG equipped the station Medicina at the Radioastronomic Observatory of the Scientific Council of Italy with the superconducting gravimeter SG-23. Continuous observations have been carried out from fall 1996 to 1999. The observations have been complemented with repeated absolute gravity measurements and continuous meteorological data (temperature, air pressure, rain fall, ground water level). The combination of the superconducting registrations with the absolute gravity measurements enable to model the instrumental drift parameters of SG-23 and to determine significant gravity changes at the station (SCHWAHN et. al, 1999).

IPG performed studies on the correlation between precipitation, ground water level changes and secular gravity changes at the North Annotation Fault Zone, Turkey (GERSTENECKER, 1998, pers. Comm.)

## 6. Geodynamic research projects

Geodynamic research was mainly focussed on the monitoring of volcanoes. IAGP and IPG established a gravity repetition network at Mount Merapi, Indonesia together with the Volcanological Survey of Indonesia and Gadjah Mada University Yogyakarta Indonesia (GERSTENECKER, 1999) for the mapping of the gravity field and gravity changes associated with eruptions.

Major studies with repeated precise gravimetry, partly in conjunction with GPS measurements were made at the Mayon volcano, Philippines and the Galeras volcano Colombia by IAPG (see e.g. JAHR et al, 1997, HAASE et. al, 1995, JENTZSCH et al, 1999). Gravity networks comprise 25 stations at Mayon volcano (Philippines), 22 stations at Merapi volcano (Indonesia) and 33 stations at Galeras volcano (Colombia).

TPG (Institut für Planetare Geodäsie, Univ. Dresden) has initiated a project for studying recent vertical crustal movements in Western Greenland (DIETRICH et al., 1998).

## 7. Other related topics

In consequence of the German reunification in 1990 NLfB-GGA (Niedersächsisches Landesamt für Bodenforschung, Hannover) made further efforts to complete the gravity data base for the eastern part of Germany. On this occasion gravity values going back to campaigns between 1934-1945 (Geophysikalische Reichsaufnahme) were transformed to the I.G.S.N.71 after connecting parts of older base points to modern gravity nets and realizing the adjustment of both nets. Additional measurements have been carried out in the region of Berlin (166 stations) as well as along the former border between the two German countries (281 stations) in order to improve the data base in these areas.

Supporting a Czech – German deep-seismic working group a gravity map (1 : 500 000) was compiled, covering the area of northern Bavaria, southern Saxonia and the western part of the Czech Republic.

Based on all gravity data available, a map of the absolute gravity values of Germany was presented by PLAUMANN in 1998.

In cooperation with the Geological Surveys various investigations have been realized, dealing with local geological structures. Gravity measurements and interpretations were undertaken in order to study the Halle Fault, the top of Malm (Upper Jurassic) in Bavaria, a tertiary Maar in the vicinity of Baruth (Saxony) and the salt structure „Arendsee“ near Salzwedel. The majority of the interpretations were carried out by two- and three-dimensional gravity modelling, integrating all geophysical and geological boundary information available. The main results can be summarized as follows:

Southeast of the city of Halle a gravity survey was realized (158 new gravity stations) in order to investigate the Halle Fault being covered by 100 m of sediments. Based on this new data set, the horizontal continuation of the fault could be specified. Further results were derived concerning the base of Tertiary, showing a long-wavelength topography with an amplitude between 45 and 50 m in a depth of 70 m.

From regional gravity studies two local minima in the vicinity of Kleinsaubernitz and Baruth (Saxony, Germany) are known. The gravity low of Kleinsaubernitz is caused by 300 m limnic sediments underlying 200 m of miocene series, as could be proofed by drilling in 1970. Therefore, new interpretations proceeded on the assumption that the source of the anomaly Baruth (-7 100 nms-2) is also a tertiary maar, produced by a phreatomagmatic explosion. In 1998 two research boreholes (280 m and 100 m deep) were realized by Geowissenschaftliche Gemeinschaftsaufgaben (Hanover, Germany) in order to enable various geoscientific studies. Extensive preliminary investigations were carried out with the aim to determine the best location for drilling. The different geophysical methods applied comprise gravity (400 new gravity stations), magnetic, geoelectric and seismic surveys. Borehole measurements and VSP complemented these data sets later. A three-dimensional gravity model was developed, showing a fit of the observed and calculated gravity field better than 0.3 100 nms-2. The geometry of the geological bodies and their densities take into account the results of the different geophysical investigations. The tertiary maar of Baruth is nearly circular symmetric, its lateral extent is about 1200 m, whereas the thickness of the limnic sediments is 200 m.

In the area of Arendsee / Malm a projects dealing with the structure Arendsee and the top Malm are still in progress. In both areas under investigation additional gravity measurements have been carried out in order to complete the existing data sets (130 and 450 points reps.).

Studies on the tectonic evolution of the Harz mountains were published by GABRIEL et al. (1996, 1997, 199x).

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# Kinematic gravimetry

G. W. HEIN

BOEDECKER (1995) has outlined three different effects affecting the performance of a system used for airborne gravimetry: Mechanical stress may induce extra drift of the accelerometer. Shocks and vibrational stress may cause jumps in the readings, but no significant drift changes had been realized. The vibration rectification, an offset of the acceleration readings under the influence of vibrations, is a result of the cross coupling effect. This effect can be quite big but constant under a constant dynamic regime and therefore may be controlled by instrumental countermeasures. The third phenomenon is not a peculiar effect of the accelerometer, but of the total system: Any aircraft performs phugoid oscillations due to flight-mechanical reasons. These oscillations are in the bandwidth and amplitude of local/regional gravity variations and therefore need to be taken into account, usually by using DGPS information.

The Strapdown Airborne Gravimetry System (SAGS) method, discussed in BOEDECKER (1995) and previous papers, aimed at high spatial resolution with an inexpensive instrumentation in a light aircraft at low flight altitudes. – This results in higher frequency accelerations from flight dynamics as also from vibrations of the aircraft forced by the engine. All three axis lateral and rotational accelerations have been recorded under various conditions. In order to facilitate investigations, vibrations recorded by means of a shaker in the laboratory have been reproduced. Besides other important findings, one conclusion can be drawn from the measurements performed. The vibratory pattern is totally different at ground and in the air. Hence, meaningful tests are not possible at the ground.

In TIMMEN et al. (1998) an overview on airborne gravimetry, its potential for different types of application as well as undergoing developments was given. Depending on the type of application (geodesy, geophysics etc.) usually accuracies between ±10 and ±50 µm/s² for spatial (horizontal) resolutions of 0,5 to 10 km are required. The European AGMASCO project (see also XU, 1997a) has proved, that ±20 µm/s² over 6 to 7 km resolution can be reached. Besides the enhancements for the classical scalar gravimetry systems, new developments focus more and more on strapdown accelerometers, for which no inertial controlled platforms are necessary and which may also serve for vector gravimetry.

In HEIN (1995) a number of open and critical problems of airborne gravimetry were discussed. The most limiting factor of airborne gravimetry, i.e. high precision navigation, can be solved by using accurate DGPS position and velocity data. Open problems are mainly on the instrumental side (e.g. platform, sensor modeling), but also the understanding of aircraft motion (e.g. phugoid oscillations) has to be taken into account.

Airborne gravimetry at high altitudes induces the necessity of the harmonic downward continuation. Usually, FFT is applied for this purpose. In KELLER (1995) an alternative approach by means of discrete wavelet transform, which is numerically more efficient compared to FFT, was proposed.

In BLAHA et al. (1996) a basic idea to modify Poisson's integral for harmonic downward continuation into a convolution formula in the space domain, for which the Fast Fourier Transform can be applied, was presented. The method was applied to airborne gravimetry, motivated especially by the Greenland survey. The accuracy of data continuation from the flight-level to the ground was analysed. In particular, the influence of latitudinal extension is investigated, since the introduced convolution formula is exact only for the mid-parallel of the analysed area. The results obtained justify the conclusion that the introduced method is applicable to processing of real data. Extended quadratic areas (up to 2500 *km* x 2500 *km)* in equatorial areas and up to 500 *km* x 500 *km* in regions with latitudes about 75° can effectively be processed in one single procedure.

Linear gravity field state space models are a useful tool to model the anomalous gravity field in vector gravimetry, airborne gravimetry, inertial geodesy and navigation. EISSFELLER (1996) has solved the upward continuation problem of Markov gravity models analytically. In contrary to the standard Markov shaping filter approach the height dependency of the covariance function was strictly introduced in state space and not neglected. Using some basic integral transforms, a general upward continuation integral was derived for the n-th order Markov process and solved for the 2nd order Markov process in very detail. The features of the covariance model were analyzed and the height dependency was discussed numerically. The introduction of a height dependence leaves the filter structure without major changes. This will lead to a more realistic modeling in the case that the moving platform is driving along variable height profiles. A Markov gravity field model is a simple but useful way to handle the gravity field in Kalman filters.

The results of an investigation that deals with the feasibility of accurate vector gravimetry using the measurements of a hybrid differential GPS (DGPS)/rate bias inertial navigation system (RB-INS) was presented in MANGOLD (1997). The author claimed, that even the use of this high-accuracy modification of a strapdown INS augmented by precise DGPS does not allow one to estimate the components of the anomalous gravitation field of the Earth. This conclusion is the result of incomplete observability. GPS offers a translatory augmentation only that causes the analytical platform to align orthogonal to the true gravity vector, because the hybrid system exploits its rotatory degrees of freedom. The vertical component of the anomalous gravitation field can be extracted, but limitations have to be con-sidered. The integration of a star tracker allows the determination of the astronomical position coordinates. This sensor uses the direction cosine matrix as worked out by the hybrid DGPS/RB-INS to measure star elevation angles that refer to the plumb line. Taking the difference between the resulting astronomical and DGPS/RB-INS computed geodetic position coordinates yields the desired deflections of the vertical.rrr

In NEUMEYER (1997) first test results of the development of a superconducting airborne gravity system have been reported. Superconducting gravimeters have proofed their performance capabilities for static applications. The resolu-tion of those gravimeters goes down to the nGal range, their drifts lie within several µGal per year. The aim of the development is to adapt superconducting gravimeters for airborne gravimetry. In this context, the GFZ Potsdam has developed in cooperation with GWR Inc., San Diego a prototype airborne gravimeter (ASG 01) for which test measurements under static and dynamic environmental conditions have been performed. Comparison measurements with a Q-Flex accelerometer showed a good dynamic behavior of the ASG 01 and the cross-coupling-effect was within a reasonable range. Further enhancements and a new design based on a "straight-line-system" for the follow-on gravimeter ASG 02 are undertaken.

ABDELMOULA (1998) has reported on problems and solution strategies for airborne gravimetry. In contrast to land- and ship-based vehicles, which can reduce their velocity according to the measurement requirements, gravity experiments on aircrafts are subject to nearly fixed flight velocities and therefore the gravity signal cannot be separated from the disturbances conventionally. Investiga-tions have been undertaken to use additional sensors (e.g. barometric sensors or GPS) for the identification of the gravity anomaly signal. With the aid of stochastic air turbulence models and simulation computations using estimation filters (see also ABDELMOULA, 1998) it is examined, which requirements the sensors have to fulfill in order to compensate for the measurement errors.

AGMASCO (Airborne Geoid MApping System for Coastal Oceanography) was a EU (European Union) project. Six European research institutions participated in the project. They were GeoForschungsZentrum (GFZ) Potsdam, National Survey and Cadastre – Denmark (KMS), Uni-versity of Bergen (UoB), Alfred-Wegener-Institute for Polar and Marine Research (AWI) Bremerhaven, Uni-versity of Porto (UoP), and Technische Fachhochschule (TFH) Berlin. The goal of AGMASCO was to establish a European operational airborne remote sensing system for gravimetric and oceanographic applications. Employed hardware was: GPS, aerogravimeter, radar/laser altimeter, Inertial Navigation System (INS), and a strapdown system (three dimensional accelerometer sensor block). Within the campaigns, multiple static GPS reference stations and two airplane fixed GPS stations have been used to monitor the kinematic movements of the airplane. Kinematic position with precision of about 1-10 cm for survey area extension of 150-400 km, velocity with accuracy of 0.3 cm/s, could be achieved. The kinematic GPS results have been used to derive the airplane acceleration influence on the airborne gravimeter. An accuracy of 3 – 5 mGal and a spatial resolu-tion of 6-10 km, is obtained (XU, 1997a).

The carborne gravimetry campaign was a GFZ Potsdam and BGR Hannover joint campaign conducted in northern Germany at the end of 1993. The goal of the campaign was to test the carborne gravimetry system by using kinematic GPS monitoring the movement of the car. Employed hardware was: GPS, sea-gravimeter KSS31. Several days survey were carried out in November 1993 in northern Germany along three highway traverses (Hannover – Bremen – Cuxhaven, Hannover – Potsdam, Potsdam – Witt-stock – Rostock). Within the campaign, multiple static GPS reference stations and two van-fixed GPS receivers have been used to monitor the kinematic movements of the gravimeter. The distance between the two van-fixed antennas was 1.5 meter which served as an external check of the quality of GPS positioning. Velocity of the van was about 75 km/h. For a resolution of the gravity field of 1 mGal/km, accuracies of 1 m (height), 7 cm/s and 0.001 $cm/s^2$, respectively, are required. The kinematic GPS results have been used to derive the movement acceleration influence on the carborne gravimeter. An accuracy of 5-10 mGal and a spatial resolution of 6-10 km, was obtained. For an open area, using airgravimeter (able to measure also the horizontal acceleration), or sea-gravimeter (omit the long and cross acceleration of the platform), carborne gravimetry system is practically applicable (XU, 1997b).

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# Global gravity field modelling

T. GRUBER

## Introduction

The determination of the global gravity field is one of the key issues to improve the understanding of global geophysical processes in different spheres of the Earth. In geodetic science global gravity field models are the basis for regional and local geoid computations. From a global model a global height system can be defined, which interconnects all the existing continental and regional systems. Further-on, the quality of the gravity field model is one of the limiting factors for the orbit restitution quality of low flying satellites, which propagates into many different remote sensing applications (e.g. altimetry, SAR interferometry). By inferring density structures from gravity field irregularities, a view into the Earth's interior with its thermal and compositional differences can be done. Together with other geophysical data and models the gravity field is one of the main parameters for general global Earth models. By analyzing the oceanic geoid, derived from gravity field solutions, together with satellite altimeter data, the sea surface topography can be determined geometrically. This quantity is the essential information to derive the mean oceanic circulation pattern and the hydrostatic pressure field, which are strongly related to the global climate change. The determination of temporal variations of the gravity field, which are an indicator for mass redistributions in or on the Earth, will play an important role for future global change research. Large scale mass redistributions from the cryosphere to the oceans, which are predicted, can be detected in future by new observational concepts from satellites.

The determination of global gravity field models is based on different data sources. Basis for all models are observations of different types to various satellites with different orbital characteristics. From such observations the long wavelengths of the Earth gravity field (>1000 km) can be determined with an accuracy of 10 cm and better. Terrestrial gravity observations, airborne gravimetry and satellite altimetry over the oceans provide additional information for the medium and short wavelengths. Data sets with nearly global coverage are available with a spatial resolution of 30'x30'. By combining this data with satellite-derived gravity field models, the computation of high resolution models up to degree and order 360 with a mean geoid accuracy of about 70 cm can be performed. The main problem of combined models is the proper weighting of the different data sets, such that the good long wavelength information from the satellite data and the good medium and short wavelength information from the surface data complement each other and don't destroy their good properties in the different scales.

During the period from 1995 to mid 1999 theoretical and practical work in the field of global gravity field modelling has been done by different institutions. This paper summarizes recent advances and developments in Germany during this period.

## Global modelling techniques

Historically, global gravity field models are computed in terms of coefficients of a spherical harmonic series up to a specific degree and order (N), what corresponds to the maximum wavelength of the series (40000 km/N). Coefficients can be computed by numerical quadrature (numerical integration) or by a least squares approach. Satellite observations are distances and distance changes measured from ground to the satellite with laser or microwave tracking systems or directional observations with cameras. GPS observations between satellites provide continuous range and range rate observations (satellite-to-satellite tracking), which can be used as homogenous data sets for gravity field determination. Gravitational accelerations cannot be measured by these tracking systems directly. By analyzing the gravitational perturbations acting on the satellites with a least squares approach, the spherical harmonic coefficients of the series are estimated. Surface data, which represent direct observations of gravity accelerations (in case of gravimetric data) or the geoid (in case of altimetry data), in contrast, can be analyzed by numerical quadrature or again by a least squares approach. Combination of satellite data with surface data then is done by combination of the spherical harmonic coefficients (e.g. WENZEL, 1998 and 1999) or by combination of normal equations from the least squares adjustments (Gruber et al., 1995, 1996 and 1997). For the quality of the final combination model the weighting scheme for coefficients or normal equations for each data source is essential.

If least squares approaches are used for gravity field determination the maximum degree and order is limited by available computer resources, when spherical harmonics are used for gravity field representation. STRAKHOV et al. (1995, 1996, 1997 and 1998) introduced in analogy to spherical harmonics new linear approximation functions, which are also harmonic outside of a given sphere. The method is called "Strakhov's New Analytical Approximation Method" (SNAP). Starting with the integral equation of Whittacker for a harmonic function outside the sphere, trigonometric polynomial functions are introduced to represent the gravity potential (STRAKHOV et al., 1998). Using these functions for gravity field determination, very efficient recursive computations of single matrix elements can be performed, such that the maximum resolution can be extended significantly with respect to the classical spherical harmonics approach, without the need for additional computer resources. First results for regional applications show, that this new approximation method is very efficient and without loss of accuracy with respect to regular spherical harmonic series.

Spherical harmonics are frequency localizing. This means, that if only one observation on the sphere changes its value, all coefficients are influenced and the complete series has to be recomputed. From this drawback of spherical harmonics when using surface data a new mathematical model to represent the gravity field with spherical wavelets has been developed by (BAYER et al., 1998; FREEDEN et al., 1997, 1998 and 1999; WINDHEUSER , 1995). Because wavelets are space localizing they are very efficient when approximating the disturbing potential from surface gravity data. Pointwise or regional changes in surface data will only affect specific wavelet coefficients, representing the specific area. To show the efficient use of spherical wavelets for global gravity field representation the EGM96 spherical harmonic series was transformed into harmonic wavelet coefficients (FREEDEN et al., 1999). To combine advantages of spherical harmonics when analyzing satellite data (relation of gravitational perturbations of a satellite with orders of spherical harmonic series) with advantages of spherical wavelets when analyzing high resolution surface data (relation of wavelet coefficients with data localization) a concept was developed by (FREEDEN et al., 1997).

## Earth gravity field models

During the reporting period several gravity field solutions have been computed. Activities to derive new satellite-only solutions with new satellite tracking data as well as activities to generate on this basis new long wavelength and high resolution combination models have been performed and are ongoing.

## Satellite-only models

The GRIM4 satellite-only model update, which is a common effort by the GeoForschungsZentrum Potsdam (GFZ) and the Groupe de Recherche de Géodésie Spatiale (GRGS) was ongoing. Starting from the baseline GRIM4 -S1 solution, new satellite observations were included to generate the GRIM4-S4 model (SCHWINTZER et al., 1997). The model is derived from tracking data to 34 satellites in sum. With this model a considerable improvement with respect to the first GRIM4 solutions has been achieved through the inclusion of new and additional DORIS doppler data, GPS satellite-to-satellite tracking data and altimeter cross-over differences as tracking information (SCHWINTZER et al., 1995; KANG, 1998). The model is complete to degree and order 60 of a spherical harmonic series plus some few resonance terms for orders up to 70. Quality of this model is comparable to the U.S satellite-only models of the JGM and EGM96 series.

In 1995 the first GFZ satellite (GFZ-1) was put into orbit from the Russian MIR station (KÖNIG et al., 1996). This small passive cannonball satellite is equipped with a set of laser retro-reflectors for laser tracking. Due to its low altitude and its high sensitivity to gravity disturbances, additional resonant orders above 70 could be estimated. Updated GRIM4-S4 solutions including this data have been computed (CHEN et al., 1997, GRUBER et al., 1997, KÖNIG et al., 1999) and analyzed. Quality, especially for the resonant orders 16,31,46,62 and 78 could be further increased with respect to the GRIM4-S4 base model.

In preparation of the CHAMP small-satellite mission for gravity and magnetic field recovery (REIGBER et al., 1996; REIGBER et al., 1999) a complete reprocessing of all satellite tracking data has been started in 1998 by GFZ and GRGS, with the goal to generate a new GRIM5 satellite-only model. Step 1 processing, performed in 1998, includes the processing of tracking data from the main satellites to get a new global set of station coordinates and velocities and to estimate simultaneously some low degree gravity field parameters, its linear trends, and geocentric variations (SCHWINTZER et al., 1998). Step 2 processing, which is currently ongoing and will be finished in mid 1999 includes the processing of tracking data from all satellites, considered to be necessary for a complete gravity field. As new tracking data type, which was not included in the GRIM4-S4 solution, PRARE range and range rates for ERS-2 will be included. The first GRIM5 satellite-only gravity model will be extended up to degree and order 100 of a spherical harmonic series with some resonance orders up to order 120.

## Combined and high resolution models

Based on satellite-only models for the long-wavelengths, so-called combined gravity models are computed by inclusion of terrestrial gravity data and altimetric observations. Combined models can be subdivided into long wavelength solutions up to degrees about 100 and high resolution models up to degree 360. The major difference between combined and high resolution models is the modelling technique. Because of the huge number of spherical harmonic coefficients to be estimated for high resolution models, special techniques have to be applied. In contrast, the combined models usually are computed by a least squares approach, combining normal equations from the satellite-only models with normal equations generated from surface data (gravity, altimetry).

Besides the mean surface gravity data, available from BGI or NIMA, altimeter data have to be processed into mean geoid heights or altimetric gravity anomalies. High resolution mean sea surfaces were computed from geodetic phase altimeter data from ERS-1 and GEOSAT (ANZENHOFER et al., 1995 and 1996; GRUBER et al., 1995). By subtracting a sea surface topography model, oceanic geoid heights are computed and can be used as gravity field information. By inverting altimetric geoid heights or altimetry derived vertical deflections to altimetric gravity anomalies and combination of them with land gravity anomalies a nearly global consistent set of the same data type is available. Such quasi-global altimetric gravity anomalies also were derived from ERS-1 and GEOSAT geodetic phase altimeter data (RENTSCH et al., 1997, 1998 and 1999). From the global gravity field modelling point of view the combination of consistent data types is much easier than the combination of geoid heights over ocean with gravity anomalies over land (weighting, altimetry-gravimetry boundary value problem).

In the framework of the GRIM4 modelling also a combined model GRIM4-C4, complete to degree and order 72, which is based on the GRIM4-S4 satellite-only solution was computed (SCHWINTZER et al., 1997). This model combines gravity anomalies over land (OSU90 and BGI), altimetry derived geoid heights over oceans (GEOSAT/TOPEX/ERS-1 data) and the GRIM4-S4 satellite-only normal equation system. When modelling a high resolution gravity field by the least squares approach, as first iteration step, combined gravity field models based on the full variance-covariance matrix up to degree and order 100 are computed (GRUBER et al., 1995 and 1997). Different scenarios for combining gravity anomalies over land with gravity anomalies or geoid heights over oceans were investigated. There, problems of specific data sets and problems when combining different data types could be identified. Within the GRIM5 project again a combined solution up to degree and order 120 is in preparation by GFZ and GRGS and will be finished mid 1999 together with the first satellite-only model.

Based on the long wavelength combined models (with full variance-covariance matrix) as second iteration step in the least squares approach high resolution models up to degree and order 360 were computed (GRUBER et al., 1995, 1996 and 1997). For this the block-diagonal technique was used, which reduces the normal equation structure to a block-diagonal system, if regular, consistent and complete data sets are analyzed and if the longitude independent weights are applied. The block-diagonal normal equation system then is solved together with the full normal equation system of the combined base model by a rigorous block-matrix approach to compute the spherical harmonic coefficients up to degree and order 360. Overall quality of recent models is similar to the American EGM96 model.

Another approach using an iterative numerical quadrature for computing ultra-high degree gravity field models up to degree and order 1800 was introduced by WENZEL (1997, 1998 and 1999). Two models were computed from a worldwide set of 5'x5' free-air gravity anomalies, which is composed of measured and predicted gravity anomalies. Measured data are available in Europe and some other smaller continental areas and mainly over the oceans derived from satellite altimetry (75%). For most of the other areas 5'x5' anomalies are predicted from the NIMA 30'x30' mean gravity data set. Because the long wavelengths are badly resolved by numerical quadrature, for the final models all coefficients up to degree and order 20 were taken from the EGM96 gravity field solution. In contrast to the least squares approach in this case not normal equations, but coefficients from different solutions are combined. Due to the high resolution of the spherical harmonic series, comparisons to point geoid or gravity data perform very good, while orbital fits show a degradation of quality for the longer wavelengths.

To interpret the observed gravity data with respect to mantle dynamics and structures, the lithosphere-induced anomalous gravitational potential, which is generated by topographic surface loads and its isostatically compensating masses has to be removed. KABAN et al. (1999) used empirical admittances between the preliminary isostatically reduced gravity data and topographic heights for 9 major tectonic blocks of the Earth to estimate the effective depth of the remaining compensating masses. Results of this global isostatic gravity field solution show that compensation depths are varying between 20 and 50 km (Africa, North America). This demonstrates, that real isostatic compensation differ significantly to models like Airy, Pratt or Vening-Meinesz.

## Future prospects

Current and future work in the field of global gravity field modelling in Germany heavily is driven by the upcoming CHAMP small-satellite mission (REIGBER et al., 1996 and 1999). With this mission, which will provide a quasi global consistent data set of high-low satellite-to-satellite tracking data and direct measurements of the non-gravitational forces from an on-board accelerometer system over 5 years, more than one order of magnitude improvement for the long-wavelength geoid components is expected. In addition for the first time the very long-wavelength gravity field variations can be measured from space. At GFZ an operational processing system for gravity field determination with CHAMP data is under development and will be ready at launch date end of 1999 / begin of 2000. Basis for the CHAMP gravity field models are the GRIM5 satellite-only and the combined models. In the frame of CHAMP also a number of projects have been initiated at German universities, which are investigating alternative approaches for gravity field analysis from high-low satellite-to-satellite tracking data, new parametrizations of the gravity field and methods for gravity field validation.

For the U.S./German gravity field mission GRACE during the next years, together with NASA / JPL and University of Texas / Center for Space Research, GFZ will design and implement the science data system for operational processing of gravity fields up to medium resolutions (degree 150). The mission consists of two identical satellites, which measure the inter-satellite distance changes caused by gravitational field variations with extreme accuracy, and which measure the non-gravitational forces with on-board accelerometers. Together with the on-board GPS receiver this satellite constellation provides continuous high-low and low-low satellite-to-satellite tracking data. Further improvements of 1-2 orders of magnitude with respect to the CHAMP solutions are expected, what means, that gravity variations can be measured even for wavelengths up to 1000 km (degree 40).

The satellites will be launched in mid 2001.

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# Regional and local gravity field modelling

H. DENKER

## Summary

The present report describes German contributions to regional and local gravity field modelling in the period 1995-1999. The first section on theory and modelling includes studies of boundary value problems, alternative modelling techniques based on point masses and wavelets, the theory of height systems and prospects of new satellite gravity field missions. The efficient evaluation of surface integrals is discussed in section two on numerical techniques. The role of digital terrain models and the efficient computation of terrain effects is described in section 3. The last section covers different projects and practical results including the European geoid computation and various regional and local geoid and gravity studies.

## 1. Theory and modelling

Boundary value problems play an essential role in gravity field modelling and are studied in several publications. GRAFAREND and KELLER (1995) discuss different boundary value problems and derive the boundary observation functionals in gravity as well as in geometry space. In GRAFAREND and KRUMM (1996) the Stokes and Vening-Meinesz functionals are developed in a moving tangent space. A solution of the Stokes boundary value problem on an ellipsoid of revolution is provided in Martinec and GRAFAREND (1997a). The condition for a unique solution is discussed, and the ellipsoidal Stokes function is expressed using a series development on the basis of the first eccentricity of the ellipsoid. A corresponding approach is applied to the Dirichlet boundary value problem in Martinec and GRAFAREND (1997b). The upward-downward continuation of harmonic functions is investigated in GRAFAREND and KRUMM (1998) using the Abel-Poisson integral. Emphasis is put on the study of the errors introduced by planar approximations. The upward continuation is also studied by EISSFELLER (1996) using Markov type anomalous gravity potential models. A covariance model is provided and analytically and numerically investigated in view of an application to Kalman filtering. NEUMAYER (1998) investigates the shaping-filter modelling technique for the upward continuation problem, attempting to bridge the gap between classical harmonic upward continuation and Kalman filtering. The mixed altimetry-gravimetry problem for geoid determination is investigated in LEHMANN (1999) regarding the choice-of-norm problem and linearization errors inherent in standard procedures. LEHMANN (1995) investigates the approximation of the gravity field using point masses in free depths and least squares optimization to find the magnitudes and the depths of the masses. Theoretical and numerical properties of the algorithm are studied. RUMMEL (1997) and RUMMEL and VAN GELDEREN (1995) discuss the spherical spectral properties of the Earth's gravitational potential and its first and second derivatives based on the Meissl scheme. An efficient global spherical harmonic computation by 2D FFT methods is studied in SNEEUW and BUN (1996).

Much progress was also made in the use of wavelets in physical geodesy. As this topic is mainly related to IAG section IV, we mention here only some overview publications (see e.g. CUI 1995, FREEDEN 1999, FREEDEN et al. 1998a, FREEDEN et al. 1999a, FREEDEN et al. 1995, FREEDEN and SCHNEIDER 1998a,b, FREEDEN and WINDHEUSER 1997, SCHNEIDER 1997, SCHREINER 1996, WINDHEUSER 1995a,b). Further details can be found in BAYER et al. (1998a,b), BRAND et al. (1996), FREEDEN et al. (1998b,c), FREEDEN et al. (1999b), FREEDEN and SCHNEIDER (1998c), FREEDEN et al. (1997), FREEDEN and WINDHEUSER (1995), and SCHNEIDER (1996).

The theory of height systems is discussed in several publications, especially with regard to the combination with GPS ellipsoidal heights. Height systems and reference surfaces as well as the holonomity problem are discussed in GRAFAREND et al. (1995). Details about the official German height system (so-called NN system) and the transformation into other height systems are given in GRAFAREND et al. (1996a), LELGEMANN and PETROVIC (1997), and GROTE et al. (1995). The curvature and torsion of the plumbline are derived in GRAFAREND (1997), and conclusions are drawn with regard to the combination of gravity field related heights with GPS ellipsoidal heights. The gravity potential $W_0$ is computed in GRAFAREND and ARDALAN (1997) on the basis of 25 Finnish GPS and levelling (orthometric heights in Finnish Height Datum N60, epoch 1993.4) points. The Unification of different height systems in Indonesia is studied by KHAFID (1998).

At present, long wavelength errors of the existing global geopotential models are one of the major limitations for precise regional gravity field modelling, especially geoid/ quasigeoid modelling. Probably this situation can be improved only by future dedicated satellite gravity field missions, such as CHAMP, GRACE, GOCE, etc. A study in this direction is given in LELGEMANN and CUI (1999) considering satellite-to-satellite-tracking data from CHAMP and GRACE. Furthermore, the future missions CHAMP, GRACE, GOCE and STEP are studied in BALMINO et al. (1998), MÜLLER et al. (1997), SNEEUW et al. (1996) and SNEEUW and ILK (1997). All these mission have the polar gap problem (because they fly not directly over the poles), which is discussed in SNEEUW and VAN GELDEREN (1997). Moreover, the geodetic-geophysical contribution of future satellite gravity missions is discussed in THALHAMMER et al. (1996).

## 2. Numerical techniques

An overview on the solution of boundary value problems with modern parallel computers is given in LEHMANN (1997b). Detailed investigations on the fast space domain evaluation of geodetic surface integrals can be found in LEHMANN (1997c). The calculation of strongly singular and hypersingular surface integrals is studied in Klees and LEHMANN (1998). Boundary element methods in physical geodesy are investigated in LEHMANN (1997a). In this study emphasis is put on modern numerical cubature methods and the implementation on parallel computers. An extension of the boundary element technique through incorporation of a global reference field is described in LEHMANN and KLEES (1999).

## 3. The role of digital terrain models

Digital terrain models are important to model the short wavelength components of the gravity field and to avoid aliasing effects. ENGELS et al. (1996) derive global topographic-isostatic geoid models and compare them with observed models. Conclusions are drawn regarding the isostasy hypothesis and density functions. The constant crustal density model is considered as unrealistic. The gravitational potential of a deformable massive body generated by tidal and load potentials is studied in GRAFAREND et al. (1996b) with numerical tests being done with the Molodensky Earth model and the PREM mass density model. Further details on the spacetime gravitational field of a deformable body are given in GRAFAREND et al. (1997).

Efficient formulas for the computation of the gravitational potential and its first and second derivatives are presented by PETROVIC (1996). The formulas are obtained by transforming the basic volume integral into line integrals. An important property of the solution is that all gravity field quantities can be represented by only two different line integrals, leading to an efficient programming. Improved procedures for the computation of terrain corrections based on inclined prism tops are investigated in TSOULIS (1998a and 1998b).

The approximation of the gravity field in the central Andes region is investigated by SCHILDE (1997) with emphasis on the use of topographic data. The remove-restore procedure is applied and corrections to a global model are derived, showing a high local variability due the rough terrain. A method for the determination of the total mass and the center of gravity of a disturbing mass body is described in KROKOWSKI (1997). The method is based on a spherical harmonic expansion and is tested with synthetic and real data. The method is extended in KROKOWSKI (1999) to provide also some information on the extension of the disturbing mass body using least squares.

## 4. Projects and results

High resolution gravity anomalies are computed from satellite altimeter data at GFZ/D-PAF. For this purpose the orbits and some of the data corrections are recomputed using state-of-the-art models. Several global computations are available with a grid spacing of 3' x 3' using ERS-1 geodetic mission data (RENTSCH et al 1997a,b,c). The altimeter data are transformed to deflections of the vertical, and after gridding of these data the gravity anomalies are computed by FFT. Quality tests are performed using shipborne gravity data and altimetric gravity data grids from other researchers. The incorporation of Geosat geodetic mission data in these computations is first investigated in test areas along the Mid-Atlantic Ridge and the Azores (RENTSCH et al. 1998) and finally performed on a global basis using a 2' x 2' grid (RENTSCH et al. 1999). The separation of the geoid and stationary sea surface topography is studied in the Western Mediterranean Sea (YONG WANG et al. 1998). Gravity data are used to compute a gravimetric geoid that is then compared with satellite altimeter data to derive the sea surface topography. Similar studies regarding the computation of the sea surface topography are done for the Baltic Sea (LIEBSCH et al. 1995) and for Western Europe (DODSON et al. 1995).

The Institut für Erdmessung (IfE), University of Hannover, continued the computation of an improved high resolution geoid/quasigeoid model for Europe. IfE is acting as the computing center in this project on request of the IAG Geoid Subcommission for Europe. Since the previous IUGG General Assembly in Boulder (1995), where the solution EGG95 (European Gravimetric Geoid 95) was presented (DENKER et al. 1995b,c), status reports were given at international symposiums in Tokyo (DENKER et al. 1997), Brussel (TORGE 1996), Rio de Janeiro (DENKER and TORGE 1998), Maracaibo (TORGE and DENKER 1999a) and Budapest (TORGE and DENKER 1998a). Since 1995 significant amounts of new gravity and terrain data could be obtained including data for all countries in Eastern Europe. In the course of the project, about 2.7 million gravity data and 700 million terrain data are included in the data base. The gravity data spacing is now at least 10 km for all European land areas, while significant data gaps still exist in the marine gravity data. However, these gaps could be filled with altimeter derived gravity anomalies, leading to a more or less homogeneous data coverage for the entire computation area. Special emphasis was put on the processing of the marine gravity data and the combination with satellite altimeter data. This work is documented in the dissertation thesis of BEHREND (1999) and BEHREND et al. 1995 and 1996. The modelling strategy is based on the remove-restore technique. Terrain data are considered using the residual terrain model (RTM) procedure. The long wavelength gravity field components are taken from available global models (OSU91A, OSU91A_JGM3, EGM96). The combination of the gravity data and the global model is performed using the least squares spectral combination technique with integral formulas evaluated by 1D FFT (DENKER et al. 1995a, DENKER 1996). The geoid/quasigeoid models are calculated in a 1.0' x 1.5' grid covering the area 25°N - 77°N and 35°W - 67.4°E. This yields 3,120 x 4,096 = 12,779,520 grid points. The final model computed in the project is named EGG97 and is based on the global model EGM96 (DENKER and TORGE 1998). The EGG97 geoid and quasigeoid model are available on a CD-ROM as announced in the Journal of Geodesy (1997). The internal error estimates for height anomaly differences are ±3.9 cm over 100 km and ±7.6 cm over 1000 km distance, respectively (std.dev. of gravity data ±1 mgal, see e.g. DENKER 1998 and TORGE and DENKER 1999b). The EGG97 quasigeoid model is evaluated by a number of GPS/levelling data sets. We mention here the results from the French GPS/levelling data set of 965 control points, leading to a RMS difference of ±0.13 m for the bias fit and ±0.08 m for the bias and tilt fit. The residuals show medium to long wavelength (100 km and larger) features of a few cm/100 km and a few dm/1000 km. Such long to medium wavelength discrepancies between EGG97 and GPS/levelling data are also found in other comparisons (e.g. DENKER 1995, 1996, TORGE and DENKER 1999b), and they are most probably due to long wavelength errors of the global models and the terrestrial gravity data. These long wavelength errors can be modelled by a trend and a signal component using least squares collocation with an appropriate covariance function. For the French data set an empirical covariance function was computed, showing a variance of $(0.08 \text{ m})^2$ and a correlation length of 80 km (DENKER 1998). The signal and the trend component are finally added to form a corrector surface to the EGG97 model. After consideration of this corrector surface, the residuals in independent control points are in the order of ±0.01 to 0.02 m (DENKER 1998). This proves the efficiency of the procedure in removing long wavelength errors of the EGG97 model. Further evaluations of the EGG97 model in Germany show that over shorter distances simple fitting procedures (bias and tilt fit) are sufficient to obtain accuracies of ±0.01 ... 0.03 m over a few 100 km, while over a few 10 km accuracies of ±0.01 m are found (TORGE and DENKER 1999b). Further methodological and numerical investigations at IfE are concerning the Molodensky correction terms, being neglected so far in the computations. In these investigations emphasis is put on the use of different terrain reduction techniques. The results show an improved series convergence for the terrain reduced gravity data. Maximum effects of the Molodensky series terms are 10 cm in mountainous areas (Alps, Rocky Mountains) and 1 cm for highland areas (Harz) when using terrain reductions (DENKER and TZIAVOS 1999). In addition, local studies of the EGG97 solution were done at IfE in the North Sea region (TORGE et al. 1995, BEHREND et al. 1996), where GPS and the EGG97 model are used to transfer normal heights from the mainland to the island of Helgoland (SEEBER and TORGE 1997, SEEBER et al. 1997, TORGE 1997, GOLDAN et al. 1995a,b). Finally, IfE was also engaged in the evaluation of the EGM96 model and its predecessors (DENKER 1997).

The combination of gravity data, a global geopotential model and GPS/levelling data was investigated at the Bundesamt für Kartographie und Geodäsie (BKG), Frankfurt, using point mass modelling. In this procedure, the point gravity data are merged to mean values with a block size of 5 km (flat areas) and 2 km (low mountain ranges). The point masses are arranged at depths of 10 km and 30 km as well as at 5 km in low mountain ranges. The point masses are computed in a least squares adjustment from the gravity and GPS/levelling data. Results are available for East Germany. The residuals from the adjustment are at the level of 1-2 cm for the GPS/levelling quasigeoid heights. The accuracy of the final quasigeoid model is stated as ±1-2 cm over 100 km distance (IHDE et al. 1998). For further details see also IHDE (1995, 1996, 1997, 1998), SOMMER et al. (1996) and SEEGER et al. (1997). The BKG is also engaged in the EUVN European GPS/levelling project, which will be very useful for future continental geoid/quasigeoid calculations. Furthermore, BKG and IfE have started a cooperation on the computation of a new combined (gravity and GPS/levelling data) German quasigeoid model.

A high resolution geoid model for Germany was also computed at the Institut für Physikalische Geodäsie, TU Darmstadt (BELIKOV and GROTEN 1995, GROTEN et al. 1998) using a global model (OSU91A resp. EGM96) and about 150,000 gravity data. In the computation process a tailored global model is computed and the high frequency part of the geoid is then derived using the pseudo harmonic regional analysis (PHRA) technique. The evaluation of the such derived models is detailed in GROTEN (1996).

A local high precision gravity field model for the area of Berlin is presented in WZIONTEK and LELGEMANN (1997a and 1997b). The computation is based on point masses with a grid spacing of about 2.4 km. Furthermore, a long wavelength corrector surface is derived from GPS/levelling data with residuals in the order of ±0.01 m. The accuracy of the model is stated as ±0.005 m for the height anomalies, while the gravity disturbance vector could be computed with an accuracy of ±0.5 mgal. A transformation of the model to different reference systems is discussed in STUBENVOLL et al. (1997) as well as in WZIONTEK and LELGEMANN (1999).

KORTH (1998) and KORTH et al. (1998) present a geoid computation for parts of Antarctica considering gravity and ice thickness data in combination with a global model. The mathematical modelling is based on point masses. Another geoid determination for Antarctica is described in STEFANI et al. (1995). Furthermore, a geoid computation for Hungary is discussed in ÁDÁM et al. (1995).

In 1995 a consortium of 5 European institutions initiated the AGMASCO (Airborne Geoid MApping System for Coastal Oceanography) project supported by the EU Commission. The project is coordinated by GeoForschungs Zentrum (GFZ) Potsdam, the main objective being the development of an airborne gravimetry/altimetry system to determine the marine geoid in coastal and shelf areas (TIMMEN et al. 1998a and 1998b, FORSBERG et al. 1999). The aeroplane based system is operational which is demonstrated in several projects (Skagerrak, Fram Strait, Azores). Results in the Skagerrak area show a gravity accuracy of 20 μms$^{-2}$ and a spatial resolution of 6 to 7 km. Geoid computations based on these data are presented in KEARSLEY et al. (1998) and FORSBERG et al. (1999). Final results of the AGMASCO project will also be available on the internet (http://agmasco.gfz-potsdam.de).

An interesting development in the modelling of the gravity field is the computation of ultra high degree geopotential models. At present models up to degree and order 1800 are available using 5' x 5' and lower resolution gravity data (WENZEL 1998a,b, 1999a,b,c). The computations are based on integral formulas. The evaluation of the models by GPS/levelling data shows RMS discrepancies of some cm for the ultra high degree models as compared to some dm for the models OSU91A and EGM96 (max. degree 360). Furthermore, a regional geopotential model to degree and order 720 is developed for the Mediterranean Sea in Yang LU et al. (1999).

A new Bouguer gravity map for the southern part of Germany is derived at Niedersächsisches Landesamt für Bodenforschung (NLfB, PLAUMANN 1995b). An absolute gravity map for entire Germany is given in PLAUMANN (1998). In addition, a Czech-German gravity map is compiled, covering the area of northern Bavaria, southern Saxonia and the western part of the Czech Republic (PLAUMANN 1996a). The transformation of older gravity observations from 1934-1945 (Geophysikalische Reichsaufnahme) to the IGSN system is investigated in PLAUMANN (1995a) for East Germany. Local gravity investigations and interpretations are undertaken at NLfB in order to study the Halle Fault (PLAUMANN 1996b), the top of Malm in Bavaria (GABRIEL and RAPPSILBER 1999), a tertiary Maar in the vicinity of Baruth in Saxony (PLAUMANN 1996c) and a salt structure near Salzwedel (GABRIEL and RAPPSILBER 1999). A structural interpretation of gravity anomalies within the frame of the KTB project is given in CASTEN et al. (1997).

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# SECTION IV

# GENERAL THEORY AND METHODOLOGY

# Physical aspects of modeling in geodesy

## – Overview and highlights –

B. HECK

In the present structure of the IAG, section IV covers general aspects of geodetic theory and methodology. As such it is strongly related to the mathematical and physical foundation of Geodesy. In this respect, a great deal of work has been performed in the framework of the sub-structure of section IV, consisting of the Special Commission SCI and the Special Study Groups, devoted to the following subjects:

SCI: *Mathematical and Physical Foundations of Geodesy* (President: E. GRAFAREND, Germany)

SSG 4.169: *Wavelets in Geodesy* (Chairman: B. BENCIOLINI, Italy)

SSG 4.170: *Integrated Inverse Gravity Modelling* (Chairman: L. BALLANI, Germany)

SSG 4.171: *Dynamic Isostasy* (Chairman: L. SJÖBERG, Sweden)

SSG 4.176: *Temporal changes of the gravity field* (Chairman: D. WOLF, Germany)

The results of the scientific work have been published in international journals such as Journal of Geodesy, Geophysical Journal International, and Journal of Geophysical Research, as well as in national journals and Publication series, e.g. ZfV (Zeitschrift für Vermessungswesen), AVN (Allgemeine Vermessungs-Nachrichten) and the series of the publications of the German Geodetic Commission. Much of the work has also been presented in international symposia and national meetings. For IAG section IV the IAG Scientific Assembly which took place on Sept. 3-9, 1997 in Rio de Janeiro/Brazil had an eminent importance; traditionally the Hotine-Marussi Symposia on Mathematical Geodesy play a dominant role in the life of Section IV, as could be realized in the past meeting in Trento, Sept, 14-17, 1998. A new series of national meetings in Germany have been initiated, highlighting also the subjects investigated in Section IV bodies: *The Geodetic Week* (*Geodätische Woche*), addressing in particular to young researchers in Geodesy, has been organized at the University of Stuttgart in 1996, at the Technical University of Berlin in 1997 and at the University of Kaiserslautern in 1998.

Furthermore, a couple of International IAG schools should be mentioned, covering important topics of Section IV: International Summer School of Theoretical Geodesy on *Geodetic Boundary Value Problems in View of the One Centimeter Geoid* in Como/Italy, May 26 – June 7, 1996, International School on Data Analysis and Statistical Foundation of Geomatics in Chania/Greece, May 25 – 30, 1998 and IAG School on Wavelets in the Geosciences in Delft/The Netherlands, Oct. 4 – 9, 1998.

Geodetic theory and methodology is reflected in a number of textbooks published in the past 4-years period by German authors: In 1998 S. HEITZ and S: STÖCKER-MEIER published the 3rd edition of *Grundlagen der Physikalischen Geodäsie* (*Foundation of Physical Geodesy*), while in 1997 K.R. KOCH presented the 3rd edition of *Parameterschätzung und Hypothesentests in linearen Modellen* (*Estimation of Parameters and Hypothesis Tests in Linear Models*). The basic geodetic computation procedures and evaluation models used in classical horizontal and vertical as well as in three-dimensional networks have been presented in the 2nd edition of B. HECK's text book *Rechenverfahren und Auswertemodelle der Landesvermessung* (1995). M. SCHNEIDER completed his textbook series on Celestial Mechanics, consisting of four volumes (Vol. III 1997, Vol. IV 1998) and covering the subject in its full width and depth, from general system models to the specific modelling applied in Satellite Geodesy.

The following contributions on Physical Aspects of Modelling in Geodesy, Mathematical Aspects of Modelling, and Theory of Data Evaluation provide details on the work related to IAG Section IV which was carried out in the Federal Republic of Germany from 1995 to 1999.

The physical aspects of modelling in Geodesy cover the basic theories of Physics (Newtonian mechanics, special and general theory of relativity, quantum theory) which are applied in some way in any modelling in Geodesy. Strong advances in the past four-year period can be recognized in the fields of modelling the propagation of electromagnetic waves in refractive media, stimulated by the use of GPS observations, and modelling the orbits of low flying satellites. On the background of IERS and IGS the theory of reference frames has been further developed. Another challenge is the modelling of the time-dependent gravity field of the earth, induced e.g. by dynamic isostasy. With respect to the structure of IAG Section IV reference is provided to sub-commissions 4 and 5 of Special Commission 1 and to Special Study Groups. 4.171 and 4.176.

The mathematical part of geodetic models is related to the use of numerical and approximation methods as well as to the application of advanced mathematical tools such as wavelets, integral transforms and boundary element methods. Special emphasis has been put in the solution of inverse and improperly posed problems, in Mathematical Geodesy and Cartography and in the theoretical background and numerical solution of geodetic boundary value problems. Mathematical aspects of modelling have been intensively studied by sub-commissions 2,3 and 4 of Special Commission 1 as well as by the Special Study Groups 4.169 and 4.170.

Geodetic data cannot be completely modelled in a deterministic sense, therefore stochastic components come into play, involving statistics and adjustment theory as well as random fields in the case of continuous variables, statistical inference, including Bayesian inference, and deterministic and stochastic signal analysis can be used as further tools for processing geodetic observations. The subject of data evaluation includes reliability aspects of GIS, too. These topics have been addressed to by the subcommisison 1 of Special Commission 1.

# Physical aspects of modeling in geodesy

E. GRAFAREND

Physical Aspects of geodetic modeling were of focal interest to F. BARTHELMES, H. GREINER-MAI and H. JOCHMANN (1998), when they predicted gravity changes on the surface of the Earth due to *inner core precession.* In contrast, S. BETH et al. (1997) studied wavelet methods in edge detections and *refraction*. A special contribution of the *„Bundesamt für Kartographie und Geodäsie“* (1998) had *Earth rotation* as a central topic to which we refer. K. BÖRGER (1998) aimed at a geocentric modeling of relativistic very long baseline interferometry. B. EISSFELLER (1997a, 1997b, 1997c) developed a *dynamical error model* for GPS autocorrelation receivers and applied it in urban areas. E. GRAFAREND (1995) solved the spherical Stokes boundary value problem in a moving tangent space, namely to estimate the errors in the so-called „Flat Earth Approximation“. Similarly in E. GRAFAREND and F. KRUMM (1996) the flat Earth approximation errors were analyzed within the *Stokes and Vening-Meinesz integrals*. A review contribution on orthometric heights, namely on the *field lines of gravity*, their curvature and torsion, the *Lagrange and Hamilton* equations of the plumbline, was presented by E. GRAFAREND (1997b). $W_0$, an estimate for the regional gauge value of the equipotential surface, *the geoid*, close to Mean Sea Level, derived from twenty-five GPS points of the *Baltic Sea Level Project*, epoch 1993.4, Finnish Height Datum N60, was derived by E. GRAFAREND and A. ARDALAN (1970). The physical interpretation of the geoid was reviewed by E. GRAFAREND et al. (1996). The gravitational field of *topographic-isostatic masses* and the hypothesis of mass condensation has been analyzed by E. GRAFAREND, J. ENGELS and P. SORCIK (1995, 1996). The gravitational potential of a deformable massive body generated by *tidal and load potentials* has been studied in all detail by E. GRAFAREND, J. ENGELS and P. VARGA (1996, 1997). A detailed physical set-up of observational equations in gravity space as well as in geometry space has been worked out by E. GRAFAREND and W. KELLER (1995). In order to detect the errors in the so-called *„Flat Earth Approximation“*, E. GRAFAREND and F. KRUMM (1998) analyzed the *Abel-Poisson kernel/integral* in a moving tangent space. Due to the standard of *The International Reference Ellipsoid* (eg. WGS84), E. GRAFAREND and Z. MARTINEC (1997a, b) solved the external *Stokes* boundary-value problem as well as the external *Dirichlet* boundary-value problem on an *ellipsoid of revolution.* E. GRAFAREND and J. SHAN (1997) modeled estimable quantities in projective networks like those in photogrammetry or CCD imagery. A review of projective heights, both in geometry and in gravity space, has been set up by E. GRAFAREND, R. SYFFUS and R.J. YOU (1995). The distribution of *lunisolar tidal elastic stress* within the mantle was estimated by E. GRAFAREND and P. VARGA (1996). T. GRUBER, C. REIGBER and J. WÜNSCH (1999) estimated the ocean mass redistribution by means of *altimetry* and circulation models. J. HAMMESFAHR et al. (1999) studied the usage of two-directional link techniques in satellite geodesy. T. HARTMANN et al. (1992) analyzed the propagation of electromagnetic signals in gravitational fields and in a refractive, dispersive medium, namely applied to satellite measurement techniques. B. HECK (1995) developed concepts for terrestrial and celestial reference frames. G. HEIN et al. (1997) developed new concepts for orbit determination of geosynchronous satellites of a *European* satellite navigation system. S. HEITZ (1997) reviewed the basis of very long baseline interferometry. As a third edition, a proof of success, S. HEITZ and E. STÖCKER-MEIER (1998) published their book on *„Foundation of Physical Geodesy“*. In a first study H. JOCHMANN (1999a) analyzed the influence of continental water storage on the annual wobble of polar motion from an *inverse problem*. In H. JOCHMANN (1999b) as a second study inverse problems of type temporal variation of Earth rotation and gravity field identification were reviewed. P. JOHNSTON et al. (1999) studied material versus isobaric internal boundaries in the Earth and their influence on postglacial rebound. M. KABAN et al. (1999) presented a new global isostatic gravity model of the Earth. Deglacial land emergence and lateral upper-mantle heterogeneity in the Svalbard Archipelago were documented by G. KAUFMANN and D. WOLF (1996). The effect of *lateral viscosity variations* on postglacial rebound has been proven by G. KAUFMANN and D. WOLF (1999). A similar effect on postglacial land uplift close to *continental margins* could be shown by G. KAUFMANN et al. (1997). V. KLEMANN et al. (1998) modeled stresses in the Fennoscandian lithosphere induced by Pleistocene glaciations (1998). The same research team, namely V. KLEMANN et al. (1998) succeeded in showing the implications of a ductile crustal layer on glacial-isostatic adjustment. V. KLEMANN et al. (1999) analyzed the deformations of the Fennoscandian ice sheet. In a series of papers S. KLIONEER (1998) and S. KLIONEER and M. SOFFEL (1998, 1999) studied the role of relativity on (i) the rotational motion of an extended body like the Earth, (ii) geodetic VLBI, and (iii) precession and nutation. J. MÜLLER et al. (1995) tested Einstein's theory of gravity by lunar laser ranging. M. RABAH (1998) enhanced kinematic GPS-ambiguity resolution using a regional ionospheric model. C. REIGBER (1998) reviewed temporal gravity field variations from oceanic, atmospheric and inner core mass redistributions and their sensitivity to new gravity mission *Champ* and *Grace.* H. RUDER et al. (1997) referred to the curved geodesic with respect to Very Long Baseline Interferometry, G. RÜMPKER et al.

(1996) succeeded in viscoelastic relaxation of Burgers half space, namely for the analysis of Fennoscandian uplift. M. SCHNEIDER (1997, 1998) completed his excellent textbooks I-IV on *Celestial Mechanics*. In M. SCHNEIDER et al. (1997) the precise surveying of the Moon has been reviewed. M. SCHRAMM (1997) reviewed Newton's historical textbook „Philosphiae naturalis principia mathematica". H. SEEGER et al. (1997) highlighted the scientific targets of the *Fundamentalstation Wettzell*. We already mentioned the successful work of the research team M. SOFFEL and S. KLIONEER (1997, 1998a, b, c, d, 1999) in (i) relativistic celestial mechanics, (ii) the Nordtvedt effect in rotational motion, (iii) relativistic space astronomy, (iv) nonrotating astronomical relativistic reference frames, (v) the relativistic transfer function in relativistic nutation of a non-rigid Earth and (vi) the post-Newtonian description of rotational motion of astronomical bodies. M. THOMA and B. WOLF (1998, 1999) modeled simultaneously land uplift and secular gravity change in Fennoscandia and determined the mantle viscosity from those observations of land uplift and gravity in this area. K. WIECZERKOWSKI et al. (1998) *revised* the relaxation-time spectrum for *Fennoscandia*. J.O. WINKEL et al. (1998a, b) simulated a generic GNSS receiver in virtual environment. D. WOLF (1998) reviewed *load-induced viscoelastic relaxation*. In contrast D. WOLF and G. KAUFMANN (1998) studied the effects of compressional and compositional density stratification on load-induced Maxwell-viscoelastic perturbations. Finally, J. ZSCHAU (1997) reviewed Earthquake prediction with *Seismolap*, satellite geodesy and very-long-basis-interferometry at Wettzell.

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# Mathematical aspects of modeling

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## Abstract

Geodetic modeling includes the establishment of mathematical and physical models which describe the static and time dependent parts of the surface and the gravity field of the earth. This report summarizes the activities within the years 1995 to 1999 to develop mathematical tools and procedures to compute parameters of those models. The various contributions within this period are divided into the following sub-topics:

- numerical and approximation methods,
- advanced mathematical tools,
- inverse and improperly posed problems,
- mathematical geodesy and cartography,
- geodetic boundary value problems,
- modeling the deformable earth.

## Numerical and approximation methods

The preferred technique in geodesy to model the global gravity field is still based on solid spherical harmonics. One of the reasons is the fact that spherical harmonics are especially useful in the various techniques of classical dynamical satellite geodesy (see e.g. FREEDEN et al. (1995)). Despite the advantages of a spherical harmonic expansion, from a theoretical and numerical point of view, they show also some disadvantages. It is a well-known fact that the surface spherical harmonics build an orthogonal system of base functions on the sphere. This simplifies the expansion of a function given on a sphere. In general, the data distribution is discrete and irregularly distributed which, in general, disturbs the orthogonality relations. In case of a large number of unknowns spherical harmonic analysis becomes badly conditioned and, furthermore, is rather time consuming even by using large computers. An alternative to spherical harmonics was proposed by STRAKHOV and presented in SCHÄFER et al. (1998a, 1998b). This so-called SNAP method allows the derivation of high-resolution gravitational models using irregularly distributed discrete data not restricted to the surface of the sphere. Applications to the gravity field of the earth show the potentials of this method.

Surface spherical harmonics are base functions with global support. They show localization in frequency domain but not in space domain. Theoretically, any change of a single discrete function value will change the complete spectrum. This is unfavourable in those cases where the discrete function values themselves, their accuracy and distribution, undergoes a continuous change in regional parts. An alternative is the use of wavelets. A remarkable property is the fact that they balance localization in space domain and frequency domain. The trade-off between “space localization” on the sphere and “frequency localization” in terms of spherical harmonics is described in form of an “uncertainty principle”. This aspect is developed from the point of view of physical geodesy in FREEDEN (1998). Despite of the fact that wavelets seem to be a proper tool for the representation of regional features of the gravity field, the spherical harmonics still have a justification for the long wavelength part of the gravity field. This is the reason that a combination of spherical harmonics and a wavelet expansion will represent the future concept in earth’s gravitational determination as discussed in FREEDEN and WINDHEUSER (1997). FREEDEN and SCHREINER (1995) investigate various non-orthogonal expansions on the sphere. Three classes of examples, Abel-Poisson frames, Gauss-Weierstraß frames and frames consisting of locally supported kernel functions, are studied. This topic together with examples related to the approximation of digital terrain models is investigated in BRAND et al. (1996). The techniques are in close relation to wavelet approximation. Further publications related to the application of wavelets to various geodetic approximation and analysis problems are summarized in the section “Advanced Mathematical Tools” of this report.

The approximation of geophysical and geodetic field functions from irregularly distributed data in space is possible also with spherical spline functions. A survey on spherical spline approximation is presented in FREEDEN a al. (1997). In SCHREINER (1997) locally supported kernels for spherical spline interpolation are studied in detail. A new condition for strictly positive definite functions on the sphere is presented in SCHREINER and a hierarchical spherical spline interpolation method and its application to a given set of air pressure data is treated in SCHNEIDER (1995). The elastic response of the surface of the earth caused by surface pressure as the water load of an ocean or an artificial lake is modeled by using Navier splines in FREEDEN et al. (1996). An application of splines to the analysis of forest relevant climate data is presented in FREEDEN et al. (1998).

Besides the use of wavelets for regional representations of gravity functionals, especially for the regional geoid, alternative approaches have been applied as well. The representation of the high-frequent part of the disturbing potential by pseudo harmonic regional analysis (PHRA) is applied to the representation of the geoid in Germany on the basis of the Earth Gravity Model 1996 (EGM96) by GROTEN et al. (1998). The separation of geoid and stationary sea surface topography and the determination of mean sea level in the Western Mediterranean Sea by local harmonic functions is performed in WANG et al. (1998).

The (graphical) representation of field functions by contour lines is still very important despite of the fact that nowadays (geophysical) fields are usually represented by digital data sets. In case of random fields, this problem leads to a sampling problem on the ordinate. The optimal discretization of the ordinates of random processes is investigated in BETHGE and MEIER (1996). Sampling rules adapted to planar fields are examined analytically as well as numerically in MEIER (1997). A procedure to derive digital terrain models (with relief-dependent grid cell sizes) from topographic maps is described in MEIER and ENDLICH (1995) and demonstrated for hilly test areas. BETHGE and MEIER (1996) interpret the modeling of random fields by contour lines as fibre process. They propose an efficient numerical procedure and demonstrate it by various examples. A comparison of various techniques for approximation of sampled terrain data, as (robust) linear prediction, optimal and active splines (snakes) is performed in BORKOWSKI et al. (1997). Images with very high information density have to be generalized for some applications. One technique for that purpose, the cartographic displacement using the snakes concept, is described in BURGHARDT and MEIER (1997a,b). The publications by BETHGE (1995 and 1997) are concerned with the geometrical accuracy of planar curves and derived quantities in case of describing the curves by means of vector data.

## Advanced mathematical tools

Wavelets represent a relatively new field of research and have been applied to various problems in applied mathematics. With a time lag of a decade the very flexible tool of wavelets becomes, besides the integral transformation techniques, increasingly popular in geodetic applications. Wavelets are families of functions derived from a single function, the "mother function", by dilation and translation. In Geodesy wavelets have been applied to approximate and analyse functions defined on a real line, on the plane and on a sphere.

The wavelet transform as a tool for time series analysis is investigated in BARTHELMES and BALLANI (1996). In this paper Morlet wavelets are applied to various geophysical and geodetic time series. The transformation allows to analyse also unevenly distributed data sets and to detect temporal variations of the spectrum, as treated in BARTHELMES (1996) or in BALLANI and BARTHELMES (1996). The application of Morlet wavelets to time series of super-conducting gravimeter data is demonstrated in NEUMEYER and BARTHELMES (1996). Various applications are given and compared to alternative techniques. In PROKOPH and BARTHELMES (1996) wavelet analysis is used to detect and to localize unconformities, events or chaotic and periodic-cyclic sequences in geological time series. Flexibility is one of the advantages of wavelet transforms in signal processing and smoothing as well as in filtering applications. But this flexibility requires also experience with this technique, otherwise it leads to wrong conclusions. This problem is treated by BETHGE et al. (1997) based on examples of smoothing filters in the wavelet and Fourier domain.

Approximation and representation problems in geodesy are usually related to the sphere. The mathematical background of a wavelet theory on the sphere with special regard to geodetic and geophysical problems was investigated by W. FREEDEN and his group. The book "Constructive Approximation on the Sphere with Applications to Geomathematics" by FREEDEN et al. (1998) presents a variety of methods, recent results, as well as a unified concept for handling different types of data. An introduction into the wavelet methods for approximating harmonic functions on the sphere is given in FREEDEN and SCHNEIDER (1995c). The application to the earth's gravitational potential and its multi-resolution analysis by harmonic singular integrals is investigated in FREEDEN and WINDHEUSER (1995). An integrated wavelet concept of physical geodesy is presented in FREEDEN and SCHNEIDER (1998c). The special aspect of spherical wavelet packets and its application in physical geodesy is treated in WINDHEUSER (1995). Discretization aspects of spherical wavelet transforms are investigated in FREEDEN and WINDHEUSER (1996) and FREEDEN and SCHREINER (1998). Important in this context is the equidistribution on the sphere as investigated in CUI and FREEDEN (1997). A new approach to approximating vectorial fields on the sphere (e.g. gravity vectors) from given data by wavelets is presented in BAYER et al. (1998). Important requirements of the application of wavelets to practical problems are fast and stable numerical techniques. A strategy for a fast multi scale evaluation of geopotentials by harmonic wavelets is presented in FREEDEN et al. (1998). Spherical panel clustering and its numerical aspects are treated in FREEDEN et al. (1998) and a pyramid scheme for spherical wavelets is presented in SCHREINER (1996). A high-resolution representation of the geoid for Germany based on the Earth Gravity Model 1996 (EGM96) by spherical wavelets is demonstrated in FREEDEN (1998b).

Wavelets are not only a proper tool for representing the gravity field of the earth. Various other potential and vector fields of the system earth can be modeled based on wavelets. An overview of geophysical modeling by multi resolution analysis is given in BAYER et al. (1998). An important application of wavelets in this context is the representation of the magnetic field of the earth. Spherical vectorial wavelets are applied to the direct approximation of vectorial data of the magnetic field enabling the decomposition into the gradient and the non-gradient part of the magnetic field in MAIER and BAYER (1998). Metaharmonic wavelets are introduced for constructing the solution of the Helmholtz equation corresponding to Dirichlet's or Neumann's boundary value problem in FREEDEN and SCHNEIDER (1997). Wavelet approximation on closed surfaces and their application to boundary value problems of potential theory is investigated in FREEDEN and SCHNEIDER (1998).

The relation between wavelet analysis and energy spectra and structure functions respectively is shown in BETH and

BOOS (1998). An interesting application in this respect is the turbulence analysis from image sequences important for the determination of the refraction coefficient. This aspect together with various others is investigated in BETH and FREEDEN (1997). Wavelet methods in edge detection and refraction are investigated also in BETH at al. (1997) and in NUTZ (1998). The determination of the atmospheric refraction from CCD camera images within the frame of uni- and multivariate Legendre-wavelets for the determination of the refraction index gradient is investigated in BETH and VIELL (1998).

## Inverse and improperly posed problems

Inverse and improperly posed problems in geodesy occur in three main applications: (i) inverse gravity modeling; detection of the mass structure of the earth's interior from gravity functionals at the earth's surface or in the outer space, (ii) downward continuation of gravity field information; derivation of gravity field parameters from smoothed or damped gravity field functionals, (iii) dynamic inverse problems; derivation of parameters which model the multibody force function of a dynamic system including the earth.

In principle, any method to determine gravity field parameters from satellite observations is a downward continuation problem and, therefore, unstable or improperly posed. The problems arising from this fact were usually overcome by including additional a-priori gravity field information in the adjustment procedure. The situation becomes much more critical if very precise observational functionals, as future SGG- and/or SST-data, shall be downward continued to derive the high frequent part of the gravity field. The uniqueness problem in satellite gradiometry (for continuous and discrete data distributions) is discussed in SCHREINER (1995) and FREEDEN et al. (1995). FREEDEN et al. (1997) treat gradiometry as an inverse problem and apply regularization wavelet solutions in form of a multi resolution analysis to derive the global and local gravity field of the earth. The latter aspect was investigated also in FREEDEN et al. (1998) with respect to applications in future problems of satellite geodesy, especially SGG. Many regularization procedures are based on filtering techniques; also multi resolution techniques show a similar effect. A regularization technique based on the combination of spherical splines with numerical filtering was investigated in SCHREINER (1995), see also SCHNEIDER (1996). The complete inverse modeling of the gravity field requires the modeling of its harmonic and anharmonic parts. In MICHEL (1998) the harmonic part is proposed to be modeled by a special wavelet based multi resolution while the anharmonic part can be treated with a new spline based method. Information measures for global geopotential models are discussed in LEHMANN (1996b). The maximum entropy principle of information theory is applied to develop a general regularization strategy for ill-posed inverse problems in LEHMANN (1999a).

The inverse gravity modeling problem can be solved by proper additional hypotheses, e.g., by an isostatic model, with which the solution space can be reduced. A major improvement in this respect is made by incorporating dynamic models of the earth interior and, indirectly, by incorporating results of seismic tomography. The contribution by THALHAMMER et al. (1996) focuses on the interface towards geodynamic use of the earth's gravity field. The application of wavelets as an instrument to solve the inverse gravimetric problem is demonstrated in BALLANI (1995).

Another downward continuation problem, important for the interpretation of certain period ranges of the earth's rotation, is the downward continuation of the variable magnetic field through the mantle to the core-mantle boundary. This problem is investigated in BALLANI et al. (1998).

## Mathematical geodesy and cartography

The basic geodetic computation procedures to determine three-dimensional networks are systematically presented in the second improved edition of HECK's text book “Rechenverfahren und Auswertemodelle der Landesvermessung” (1995). The contents cover the various relevant earth fixed coordinate systems, the basic models of “integrated geodesy” and “three-dimensional geodesy”, but also two-dimensional coordinate computations on the sphere and on the ellipsoid of revolution as well as the various (one-dimensional) height systems. The text book describes, from a modern point of view, those procedures which are still important for the establishment of modern control networks and gives credit also to those techniques which led to the basic networks still in use nowadays.

A geodetic datum transformation in three-dimensional Euclidean space based on a ten parameter conformal group is presented in GRAFAREND and KAMPMANN (1996). The transformation leaves locally angles and distance ratios form-invariant. GRAFAREND and SHAN (1996) present a closed-form solution of the nonlinear pseudo-ranging equations as they appear in satellite positioning with GPS. The transformation between two-dimensional curvilinear geodetic coordinates referring to a local geodetic coordinate system and the geodetic coordinates of a global geodetic coordinate system is investigated in GRAFAREND et al. (1995).

The definition of a height datum requires conventions about the value of the gravity potential for the reference surface. GRAFAREND and ARDALAN (1997) derive this value for the Finish Height Datum N60 from twenty-five GPS points of the Baltic Sea Level Project. A differential geometric discussion of the field lines of the gravity field with respect to the transformation of ellipsoidal heights into orthometric heights is presented in GRAFAREND (1997). The curvature and the torsion of the plumblines are investigated and the differential equations for the plumblines established. A discussion of projective heights in geometry and gravity space from the viewpoint of differential geometry can be found in GRAFAREND et al. (1995).

Estimable quantities in projective networks are discussed in GRAFAREND and SHAN (1997a). Applications are projective networks as they appear in photogrammetry, computer and machine vision as well as in robotics. The three-dimensional resection problem in terms of Möbius barycetric coordinates is solved by means of a new algorithm in GRAFAREND and SHAN (1997b).

The special problem of computing efficiently the lengths of meridians are reported by KUTTERER (1998). Systems of parameters on a three-axial ellipsoid are discussed by KRÜGER and RÖSCH (1998).

An algorithm for the inverse of a multivariate homogeneous polynomial of degree n, used in various geodetic problems, is presented in GRAFAREND et al. (1996). The algorithm is available in form of a symbolic computer manipulation program. Various cylindric map projections of the ellipsoid of revolution are investigated in GRAFAREND and SYFFUS (1997c). The Hammer projection on the ellipsoid of revolution in different variants is investigated in GRAFAREND and SYFFUS (1997a) and the generalized Mollweide projection of a biaxial ellipsoid is discussed in GRAFAREND and HEIDENREICH (1995). Similarities between Newton's equation of motion and a geodesic on a two-dimensional Riemann manifold are discussed in GRAFAREND and YOU (1995). The oblique azimuthal projection of geodesic type for the biaxial ellipsoid and the use of Riemann polar and normal coordinates is analysed in GRAFAREND and SYFFUS (1995). A strip transformation formula of conformal coordinates (Gauß-Krüger or UTM coordinates) in terms of bivariate polynomials up to degree five is derived in GRAFAREND and SYFFUS (1997d). The direct and inverse equations for a datum transformation of conformal coordinates of type Gauß-Krüger or UTM from a local datum to a global datum are given also in terms of bivariate polynomial representation in GRAFAREND and SYFFUS (1998a). The direct generation of ellipsoidal Gauß-Krüger conformal coordinates (or the transverse Mercator projection) based on the solution of the Korn-Lichtenstein equations of conformal mapping is demonstrated in GRAFAREND and SYFFUS (1998b). The optimal universal transverse Mercator projection and the oblique projection of the ellipsoid of revolution are analysed in GRAFAREND (1995) and ENGELS and GRAFAREND (1995). The optimal Mercator projection and the optimal polycylindric projection of conformal type are studied for Indonesia in GRAFAREND and SYFFUS (1998e).

Map projections of project surveying objects and architectural structures are discussed in a series of papers: GRAFAREND and SYFFUS (1997b,e, 1998c,d).

## Geodetic boundary value problems

Geodetic boundary value problems can be divided in fixed, scalar and vectorial free boundary value problems. The boundary surface is considered known in case of the fixed problem. This case is very realistic nowadays, because precise GPS-positioning provides the surface of the earth with an accuracy sufficient for many applications. The free boundary value problem can be formulated either as a scalar problem, where only the vertical position is unknown, or a vectorial problem, where the boundary is considered to be completely unknown. All these originally non-linear problems can be linearized using approximations for the boundary surface and the gravity field. While the fixed problem needs only an approximation for the gravity field, a reference or normal field, the free boundary value problems need approximations for the gravity field and for the geometry of the boundary. In case of Stokes's problem the boundary surface is an equipotential surface near an idealized sea surface, the geoid; the approximations for gravity field and boundary geometry is a reference gravity field and a level ellipsoid as approximate boundary surface (in the sense of Somigliana-Pizzetti). In case of Molodensky's problem the boundary surface is the earth's surface; the approximations for gravity field and boundary geometry is again a reference field and the telluroid respectively (classical geodetic boundary value problem). Besides a linearization another approximation is usually introduced, the spherical approximation, which considerably simplifies the computation formulas. In view of modern accuracy demands this approximation is not sufficient anymore. A systematic presentation of the various types of boundary value problems in the context of a setup of observational functionals in gravity space as well as in geometry space is given in GRAFAREND and KELLER (1995). A review of the solution procedures for geodetic boundary value problems in view of the one-centimeter-geoid is given in LEHMANN (1997a). A discussion of the three classical formulations of the geodetic boundary value problem, namely the scalar and vectorial Molodensky problem as well as the fixed gravimetric boundary value problem, from the observables to the mathematical model is presented in HECK (1997). Linearization procedures for the solution of the free and the fixed boundary value problems are reviewed in HECK (1995). Non-linear effects in the geodetic version of the free geodetic boundary value problem based on higher order reference fields is investigated in HECK and SEITZ (1997). The thesis by SEITZ (1997) focuses on the scalar free and the fixed gravimetric boundary value problem. In this context special regard is given to the ellipsoidal and topographic effects. In SEITZ (1998) the Taylor expansion point for the analytical continuation in the solution procedure of geodetic boundary value problems is investigated. Various possibilities are considered and compared. Studies on the altimetry-gravimetry problem, probably the most important mixed boundary value problem for the geoid determination are performed in LEHMANN (1999b). The geodetic mixed boundary value problem and its transformation into a system of integral equations over the boundary of the domain is treated in KLEES et al. (1997). Solution conditions are formulated and a solution strategy for all mixed boundary value problems introduced. The boundary element method permits the numerical solution of linearized geodetic boundary value problems, formulated as geodetic boundary integral equations. The report by LEHMANN (1997d) investigates various aspects of the application of this method in physical geodesy. Fast strategies for the evaluation of geodetic surface integrals in the space-domain are discussed in LEHMANN (1997c). Adequate computation facilities for the numerical evaluation of these integrals are based on parallel computers. A review of its use for these problems and for solving geodetic boundary value problems is given in LEHMANN (1996a, 1997d). A parallel setup of a Galerkin equation system for a geodetic boundary value problem, necessary for the efficient application of parallel computers, is presented in LEHMANN und KLEES (1996). The calculation of strongly singular and hypersingular surface integrals, important in this context, is treated in KLEES and LEHMANN (1998).

GRAFAREND (1995) solves the spherical Stokes boundary value problem in a moving tangent space to open the way for the application of Fast Fourier and Wavelet Transforms. Yet this was possible only in longitudinal direction on the sphere rigorously or in certain approximations. GRAFAREND and KRUMM (1996) reformulate Stokes and Vening-Meinesz functionals in a moving tangent space as well. Similarly, the idea is applied to the first boundary value problem by formulating the Abel-Poisson kernel and the Abel-Poisson integral in a moving tangent space by GRAFAREND and KRUMM (1998).

MARTINEC and GRAFAREND (1997) apply the concept of Green's functions to Stokes's boundary value problem based on an ellipsoid of revolution. They investigate uniqueness of the solution depending on the first eccentricity of the ellipsoid and discuss the ellipsoidal Stokes's function compared to the spherical case. Similarly, in MARTINEC and GRAFAREND (1997) the construction of Green's function to the external Dirichlet boundary value problem (first boundary value problem) is performed for the Laplace equation on an ellipsoid of revolution. The property of the ellipsoidal Poisson kernel is compared to the spherical kernel.

The gravitational field of topographic-isostatic masses and the hypothesis of mass condensation with respect to geoid computations is investigated by ENGELS et al. (1995), GRAFAREND and ENGELS (1996) and GRAFAREND et al. (1996).

In HEITZ (1997) the astrogeodetic leveling and the classical free boundary value problems of geodesy, a generalized form of Bruns' theorem is derived as well as a new non-linear formulation of the free boundary value problem of geodesy.

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# Theory of data evaluation

S. MEIER

## 1. Introduction

Without any data from experiments (measurements) no theory whatsoever can be investigated or verified. However, the acquisition and evaluation of data itself also requires theoretical considerations. The latter concern the sources of data sampling and spacing as well as precision and reliability. Methodic investigations are frequently mixed with the problems of modelling and geodata processing or directed at very specific data sets, e. g. from SAR, GPS, VLBI, or others. The evaluation of geodetic data is, therefore, a large domain both in content and methodology and not easily defined. In order to specifically differentiate the data evaluation from data processing, methodic papers, and such with a dominance of methodological problems will be discussed in the following.

From early on, adjustment calculation has been the central method for geodetic data evaluation, statistically speaking the parameter estimation in linear (more rarely in non-linear) models, including the theory of measurment errors, error propagation, stochastic modelling, statistical inference and, lastly, signal analysis and filtering. Rapid technological development has brought about a general improvement of accuracy. As a rule, random errors have diminished; so-called systematic errors (model errors) dominate; gross errors can still occur. Thus, there is at present a strong trend toward indentifying and eliminating the latter. Suitable methods called robust estimations are now being evaluated more intensively than a few years ago. Many of the current papers regarding data evaluation can be applied to this realm of topics.

Presently, a particularly innovative field of capturing mass-data is the evaluation of images. The methods of filtering, analysis, and data acquisition, for example with the help of Bayesesian statistics, and the random fields developed in digital image processing act as a stimulus also upon other more conventional areas. Furthermore, present digital data storages from images and maps of different kinds and scales as well as from administrative data, subtotalled under the term geoinformation systems (GIS), are being set up. The GIS-market is of growing economic importance. The users want dependable (thematically-structured, object-oriented) information. Their sources and, thus, also their quality are, by all means, different ones; contradictions are not at all rare. Therefore quality management requires thorough structural investigations as well as compulsive quality standards.

## 2. Parameter and error estimation

Theoretical but also practical investigations into parameter estimation, under numerical as well as statistical aspects are, now as ever, of great consideration. Based on technological development, papers about robust estimations dominate. These will be discussed in the following paragraph, others will be cited.

The geodetic network, particularly the optimally designed one and especially the one useful in the derivation of deformation rates has always been the center of classical least squares adjustment. Generally, the definition of very small deformation sizes connected to the problems of identification and datum problems poses a huge challenge. Theoretical tools for this were worked out by GRAFAREND and XU (1995, 1996 a, b), HEUNECKE (1995), GRAFAREND and SHAN (1997), SCHMITT (1997), NKUITE (1998), and further by ZHONG (1997) regarding local networks.

Different adjustment procedures can produce equivalent results. Comparative investigations, thus, are quite valuable in regard to different model prerequisites like in three-dimensional geodesy (KLEIN 1997) as well as in regard to minimum principles (KAMPMANN and KRAUSE 1995, BENNING 1995 b). To this belong also the equivalents of the adjustment principles and the extremal principles of physics. Pertinent papers were written by BURGHARDT and MEIER (1997 a, b), STRÖBEL (1997), HELLWICH (1998), HELLWICH and EBENER (1998).

The observation equations of adjustment problems should be recorded as completely as possible. For this purpose, respective theoretical preparatory work must be conducted for the advanced measuring techniques (monitoring). One example is the parameterization of GPS phase measurements (GEHLICH and LELGEMANN, 1997). For incomplete models the maximum correlation adjustment was proposed by PETROVIĆ (1997). The statistical theory of measuring errors again and again receives certain foundations, principally (SCHMIDT 1997, KOCH 1997 b), but also due to the continuous development of the digital measuring technology (SCHMIDT 1996, KUHLMANN 1996, KUTTERER 1998, CASPARY and WANG 1998, WANG and CASPARY 1998), as well as the necessity of assimilating hybrid data (BENNING 1995 a, 1998).

The two-volume work about least squares adjustment by WOLF (1996) was published in its third edition (as a revised reprint); in reference to the complete scientific work by H. WOLF, consult GRAFAREND (1998). Also in its third edition, the textbook about parameter estimation by KOCH (1997 a) has been published again. It is the first textbook published in German language which, besides all other information, contains a (short) introduction of robust methods.

## 3. Robust estimates

Robust estimates are, as a rule, to be understood as those which are insensitive with respect to gross errors (outliers). Robust estimates of parameters are frequently discussed in this restricted way (CASPARY 1996, KOCH 1996).

Robust estimates of parameters are investigated with respect to the detection of outliers in leverage points by KOCH (1996). He proposed to apply the robust Maximum-Likelihood-Estimate (M-estimate) according to HUBER (1964) and then modified the M-estimate for the named detection. Both estimates are readily computed by iterative reweighting within the method of least squares. An alternative method to parameter estimates according to HUBER (1964) was also discussed by BENNING (1996). Moreover, the robust M-estimate was derived by Bayesian inference (KOCH and YANG 1998 a). Confidence regions and hypothesis tests were obtained by the resulting posterior density. The necessary marginal distributions were computed by the Monte-Carlo integration.

CASPARY and CHEN (1995) describe the identification of linear random processes: if time series contain additive outliers the standard methods fails in most cases. Through the introduction of robust estimates of variances and covariances and the use of robust M-estimators for the model parameters the influence of the outliers can be suppressed so that the correct model can be found with high probability. The efficiency of this approach was verified by extensive simulations, and the successful strategy was transferred into the frequency domain (CASPARY and SUTOR 1996).

The robust methods for the analysis of linear stochastic processes were discussed extensively in two dissertations and enriched with new, efficient estimations: in the time domain by CHEN (1997) and in the frequency domain by SUTOR (1997). In a further dissertation by WANG (1997) filtering methods for error tolerant kinematic positioning were researched systematically. This includes such topics as statistical tests, the identification of gross errors as well as systematic errors, the estimation of variance components and the robust estimation in the Kalman filter; concerning the last topic see also KOCH and YANG (1998 b).

The so-called balanced adjustment also has a relationship to robust estimates (recent papers by FELLBAUM and KAMPMANN 1995, KAMPMANN 1997, JURISCH, KAMPMANN and KRAUSE 1997, JURISCH and KAMPMANN 1998). With their help, weak points in the geometry of networks as well as outliers in the leverage points are to be discovered. For this purpose, observation weights are transformed in "suitable" manner. This method has not been without contradiction (CASPARY 1998). The relationship to the robust M-estimate was critically investigated by KOCH (1996, pp 12-17).

## 4. Application of random fields: approximation, collocation, interpretation

Models for local, regional, and global fields which are (more or less) stochastically structured are of great importance in the geosciences. One example of approximation is the relief of the Earth's surface discretely represented by digital terrain models or conventionally by patterns of contours in topographic maps. An efficient model is the homogeneous random field. The appropriate counterpart to modelling the contours is the fibre process. Its qualities are determined by those of the random field gradient. The coupling of the fibre qualities to the qualities of terrain inclination leads to efficient procedures without any numerical differentiation (MEIER et al. 1995, BETHGE and MEIER 1996, BETHGE 1997).

Random field models often constitute the basis for prediction procedures . Advanced collocation methods are treated by KELLER (1998), MENZ et al. (1998), relations to each other, including such as the least squares adjustment, are described by MENZ and PILZ (1997), MENZ and BIAN (1998).

Significant advances were made in digital image processing. The standard random field model for the design and the construction of automatic (or semi-automatic) procedures is the Markovian one. Markov random fields have been used for a long time in digital image processing like restoration, edge detection, and segmentation. Now, more and more applications appear in image interpretation (KOCH 1995 a, b, KÖSTER 1995, KLONOWSKI and KOCH 1977), and in extraction of special objects or features from images of different kinds, e. g. line objects (HELLWICH and MAYER, 1996) or buildings (BRÜGELMANN 1998).

## 5. Reliability aspects of GIS

The current situation, problems and aspects of quality investigations as well as quality management are dealt with by ILLERT (1995), SCHEURING (1995), JOOS and BALTZER (1997), SCHILCHER (1997), CASPARY and JOOS (1998). They are further partly documented in a conference issue edited by BILL (1996). The most advanced seem to be the investigations into the purely geometric accuracy of point, line, and surface objects, particularly from vector data (BETHGE 1997): the well-known point error concept in geodesy could be extended systematically to line and surface objects.

Other aspects are under investigation, e. g. the integrity of data sets, the consistence of geometry and topology in maps respective digital models; see PLÜMER (1996), RAGIA and WINTER (1998). PLÜMER and GRÖGER (1997) provide a formal data model which allows for establishing the geometrical-topological integrity of surface objects in a GIS. The data model leads to an automatic tool able to check the consistency of a given set of data and to avoid inconsistencies caused by updates of the database.

Quality principles, parameters, and evaluation procedures for general geodata and for those in GIS in particular must be compatible with the general quality norm of "ISO 2000". A special working group "Quality" of the "Comité Européen des Responsables de la Cartographie Officielle" (CERCO; represents the national mapping agencies of nearly every European Country) is occupied therewith. Germany is a member of CERCO through the "Union of Public Surveying Authorities of Germany" and is incorporated in the working group "Quality" through the "Federal Agency for Cartography and Geodesy" (formerly: "Institute for Applied Geodesy").

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# SECTION V

# GEODYNAMICS

# Recent crustal movements and deformations

W. AUGATH

In continuation of the trends in the last report the increase in accuracy of space geodetic observations is going on and other techniques are still being replaced. Above all, horizontal crustal movements are meanwhile only determined by space geodetic observations and, due to GPS, not only on a global, but also on a regional, national and local basis. There remains a well known lack of accuracy of the height component because of configuration and tropospheric problems [e.g. VLBI: CAMPBELL (1996), GPS: e.g. GÖRRES (1996)]. The necessary time period for the determination of movements on the mm / year-level is decreasing, especially if data of permanent geodetic infrastructure is available. It can also be used for realtime or near-realtime results as well as for prediction purposes, e.g. of natural hazards. Normally the same infrastructure is used for the establishment and maintenance of modern reference frames as well as for geodynamics.

Existing historical observations are still used for an enlargement of the time basis in which movements can be determined. For this purpose, models for the combination of terrestrial and space geodetic observations have been developed. HECK et al. 1995 combine GPS-data and the existing terrestrial observations of the Karlsruhe-testnet over the Rhinegraben in a three-dimensional approach. Another field is the combination of GPS and precise levelling, which is done by a lot of authors. GROTEN et al. (1998) develop a combined model and use it for the monitoring of a large highway viaduct and a land slip area close to Istanbul.

Global organized VLBI- [e.g. CAMPBELL and NOTHNAGEL (1998)] and SLR-measurements [e.g. MONTAG et al. (1995)] still constitute the background for the yearly ITRF-solutions and at the same time the fundamental and global basis for the determination of recent crustal movements and deformations. In contrast to the last report the data of permanent GPS-stations, – very successfully organized by the International GPS-services for Geodynamics (IGS) -, has become the most important input for ITRF, including continental densifications as the EUREF-permanent-network (WEBER et al. 1997) or the IGS-densification in South-America (DREWES et al. 1998)].

In addition to the global IERS-solution, a lot of combinations of different space geodetic observations were presented [e.g. KANIUTH et al. (1998)), MONTAG et al. (1996), Dick et al. (1998)]. They allow a more detailed interpretation for recent crustal movement purposes. The increase of accuracy makes it necessary to develop more extensive models for the analysis of observations [e.g. for GPS: modelling of the antenna phase center variations e.g. Breuer et al. (1995), of multipath effects e.g. WANNINGER and WILDT (1997) or the modelling of correlations between the epochs (SCHWIEGER 1999)].

A lot of projects were continued or started in areas with active inter- and intra-continental deformation and subduction, ongoing and recently developing high elevated plateaus, crustal collision and extraction, block rotation as well as complex deformation at a multiple plate junction.

The EC-project GEODYSSEA (Geodynamics of South and South East Asia) reaches from Vietnam over Thailand, Philippines and Indonesia to Northern Australia. The results have confirmed that Indochina, Malaysia and half of Indonesia are moving independently from the Eurasian Plate and rotate around an Eulerian pole SW of Australia (e.g. WILSON and MICHEL, 1998). In CATS (Central Asian Tectonic Sciences Project) the current convergence between India and Rest-Eurasia is shown (e.g. REIGBER et al. 1998). SAGA, the South American Geodynamic Activities Project, leads to deformation rates for the Andes far lower than the average derived over the last 100 million years (e.g. ANGERMANN et al. 1997). In CERGOP, the EC-supported Central European Geodynamic Project, a basic network was observed four times (e.g. REINHART and BECKER 1998). The results (coordinates and velocities) of the stations are presented in the ITRF 96 and reach the highest possible level. The EC-project SELF (Crustal motion and tide gauge position variation at the Mediterranean Sea) is focussed on the height component and studies sea level variations around the Mediterranean Sea [e.g. ZERBINI et al. (1996) and (1997)]. It was supported by the European Vertical Reference Network (EUVN) 97-campaign [e.g. Ihde et al. (1998)]. The activities of the CASA-Project which supervises the South American-Caribbean plate boundary were continued (KANIUTH et al. 1998). DIETRICH et al. (1998) have determined crustal deformations in the Antarctica. Four campaigns were carried out under strong logistical and ionospheric conditions.

Additionally, a lot of less extended investigations were realized in active zones, e.g. in the Mediterranean area: the Calabrian Arc-Project (KANIUTH et al. 1995), the Adriatic Sea-Project (ALTINER et al. 1997), the Friuli-Project (SCHMIDT et al. 1996), the Eastern Alps-Project (VAN MIERLO et al. 1997), several projects in Western Turkey and the North Anatolian fault (ALTINER 1997) and at Gerede/Turkey (BAUTSCH and HIRSCH 1996) as well as the Dead Sea Rift-Project (FOPPE 1998).

In Northern Europe the investigations concerning Island (VÖLKSEN and SEEBER 1998) and Greenland [Möller (1996), DIETRICH et al. (1998)] were continued.

GPS-results were successfully combined with new techniques like SAR. REIGBER et al. (1999) report about a crustal deformation pattern in the Antofagasta 1995 earth quake region. It was determined by GPS and D-INSAR fitting together very well.

Permanent GPS-infrastructure in combination with communication allows realtime-positioning, as developed by LEINEN (1997) for larger distances as well as realtime supervision or realtime monitoring of stations in active regions. GALAS et al. (1997) and (1998) report about permanent GPS networks for natural hazard mitigation and volcano monitoring.

The use of traditional terrestrial observations is reduced to precise levelling. Due to the fact that no new observations have been available, only a limited number of reports could be presented. ZIPPELT (1995) summarizes the modelling strategies for recent crustal movements determined from repeated levelling epochs. In addition to that, interpretations of levelling-based results in the area of the Rhenish-Shield and the Black Forest are presented by DEMOULIN et al. (1995) and (1998). In the field of determination of height changes a trend towards the use of space geodetic techniques can be found. New projects as SELF or on Greenland (DIETRICH et al. 1998) are based on space techniques. Existing areas like the North Sea Coast are meanwhile supervised by permanent GPS-stations (AUGATH 1996). On the continental level the EUREF-subcommission plans to integrate existing repeated levelling epochs, space techniques and precise gravity into the European Vertical System EVS 2000 (AUGATH 1996) as a kinematic height reference frame.

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# Tides and other temporal variations of the gravity field

B. RICHTER

## Instrumental developments and investigations

With the upcoming new satellite missions CHAMP and GRACE, it will be possible for the first time to observe the time variable gravity field from space. Besides other sources, ocean mass redistribution is one of the major factors contributing to the overall time varying gravity signal. For estimating this time variable gravity signal, simulation and feasibility studies with altimeter, sea surface temperature and ocean circulation data have been performed by GeoForschungsZentrum Potsdam (GFZ). Monthly mean sea surface height models were computed over a period of three years combining altimetry and the corresponding mean sea surface temperature fields, which were used to remove the thermal water expansion. Based on these models monthly mass redistributions were computed in terms of water heights. The attraction of these water masses was computed and transformed into gravity field coefficients by spherical harmonic analysis with a resolution of up to degree 100 (corresponding to 400 km wavelength). By analysing the complete monthly time series, amplitudes and phase lags for each of the spherical harmonic coefficients can be detected (GRUBER et al. 1999, REIGBER et al. 1999).

In 1980 the first superconducting gravimeters (SGs) became commercially available and since then they have been operated very successfully world-wide. These instruments provide long term observations series which are essential to improved understanding of the time-dependent gravity field, especially causes of long-term gravity variations and the influence of environmental effects on gravity. However, even with the high quality of the time series there are still gaps, offsets and noise in the registration due to strong environmental effects like earthquakes; man-made disturbances from instrument maintenance and liquid helium transfer; and limitations in the long term stability of the electronic components. Experience with analysis of data has shown that apparent gravity (or drift) variations depend upon assumptions used to model and remove offsets (HARNISCH et al. 1997). Several long term experiments were performed at Bad Homburg, Germany (1995 – 1996), Miami, Florida, USA (1989 – 1990) and Boulder, Colorado, USA (1993 – 1994) where two superconducting gravimeters were operated side-by-side for at least one year to study instrumental effects. These experiments show that instrumentally induced disturbances are usually seen only in one instrument so that the undisturbed signal of the other instrument can be used to detect and correct any offsets or drift anomalies that occur. In spite of the success of these experiments, it is obviously too expensive and time consuming to operate two instruments at every location. In co-operation with GWR, San Diego, USA the Bundesamt für Kartographie und Geodäsie (BKG) these observations spawned the idea to develop a new dual sphere" superconducting gravimeter (DSG) which would combine the advantage of two in-situ registrations and the possibility of more simple and cost effective operation. The prototype has been installed in Wettzell after a short test series in Frankfurt / M. (RICHTER and WARBURTON 1998).

Different gravity signals (tides and free oscillations) were used to compare different instruments at the same location (Black Forest Observatory, Schiltach). A superconducting gravimeter was compared with a LaCoste-Romberg earth tide meter and broad-band seismometers (RICHTER et al., 1995a, 1995b; ZÜRN et al., 1995).

At GFZ Potsdam the registration of SG T018 end on October 8, 1998 after 2250 days of successful registration. After modifications it will be reinstalled in Sutherland / South Africa (DITTFELD 1999). Similar the registration series of SG 103 the first prototype of the successful compact SG series ends in Wettzell after 2 ½ years. It is replaced by the dual sphere SG-C029 (HARNISCH et al. 1999).

## Theory and data analysis

The forces of the moon and the sun (forced nutation) cause a motion of the rotation axis in the Earth fixed frame (polhodie, OPPOLZER-terms). SCHWAHN (1995) reminded that these terms must be taken into account and shows on the basis of the corresponding variation of the centrifugal force their influence on the diurnal gravimeter factors. The order is 0.5% depending from the Earth model.

There are at least two annual terms in the gravity variation: The annual tide Sa and the annual variation in the centrifugal force due to the annual term in polar motion. The global pattern of Sa has a zonal feature, whereas the latter is of tesseral character, moving around the globe in the course of a year. For central Europe sites the phase relation between these two waves is 90 degrees (SCHWAHN 1998).

To improve the capabilities of the tidal analysis program package ETERNA the tidal generating potential of sun, moon and the planets has been developed up to 12935 waves so that theoretical precision of $10^{-12}$ $ms^{-2}$ can be achieved (HARTMANN und WENZEL 1995, WENZEL 1996).

SCHWAHN (1999) suggested the separation of $M_3$ and $S_3$ by appropriate wave group formation with regards to modern potential developments.

In a study of tidal dissipation in planetary models WIECZERKOWSKI und WOLF (1997) demonstrated that the type of viscoelasticity is the dominant feature whereas the core radius and the density contrast at the core-mantle boundary is of secondary importance.

## Data interpretation and modelling

### Gravity observations

Continuous gravity registrations are used to study environmental effects of the atmosphere (air pressure, snow cover, rainfall) and the hydrosphere (groundwater, soil moisture) in various region in the world. A overview paper on the different effects is given by NEUMEYER et al. 1999. More detailed studies are given in e.g. ELSTNER und SCHWAHN 1998, NEUMEYER et al. 1998, HARNISCH und HARNISCH 1999. ZÜRN and WIDMER (1995) showed that the correction for barometric pressure in gravity data works well up to about 1.5 mHz.

The complexity of long-term gravity variations has been investigated by HARNISCH et al. (1998). Using the registration series of BKG in Bad Homburg and Boulder gravimeter factors for the CHANDLER-term have been determined. Similar investigations are undertaken with the gravity data registered by SG T018 at Potsdam (NEUMEYER und DITTFELD 1997).

To determine the secular change in gravity due to the Fennoscandia uplift or due to melting ice caps in Island models are derived at GFZ by WOLF et al. 1997,THOMA und WOLF 1998.

The University of Dresden reported on earth tide observations in Antarkia and Greenland (DIETRICH et al. 1998, SCHEINERT et al. 1998). ZÜRN et al. (1995) summarise the results of gravity observations at the geographic South Pole in a wide frequency band. The BFO describes gravity signals observed during catastrophic volcanic eruptions with frequencies of a few mHz (ZÜRN und WIDMER 1996).

### Tidal tilt and strain

WESTERHAUS (1997) reports on tidal tilt measurements along the North Anatolian fault and discusses temporal variations of tidal admittances in relation to stress changes associated with earthquakes. Tidal tilts were measured at the BFO by OTTO et al. (1998) using a 120 m differential pressure fluid tube tiltmeter. In the same observatory tides and earthquakes could be observed using direct stress measurements with Glötzl stress sensors in shallow boreholes (EMTER et al., 1996).

POLZER et al. (1996) used gravity, tilt and strain data from BFO to retrieve wobble parameters. The FCN period found is rather low (about 412 sidereal days).

### Well tides

Tidal fluctuations of the ground water level are frequently observed phenomena in confined or sufficiently deep aquifers. Tidal stress causes pore pressure variations in confined aquifers. They can be monitored by observing fluid level changes in wells that are in contact with this formation. Knowing the forcing functions, in-situ petrohydraulic rock properties can be derived (KÜMPEL et al. 1998, SCHULZE et al. 1998).

## Reviews

Several review articles on tidal phenomena, including effects on gravity can be found in the book edited by WILHELM, ZÜRN and WENZEL (1997). These articles are based on lectures presented at a seminar in Oberwolfach, Black Forest in 1994 aimed at advanced students in geophysics and sponsored by the German Geophysical Society. The subjects treated comprise: tidal potential, tidal response of the earth, tidal analysis, earth tide observations, nearly diurnal free wobble, ocean tides, tidal loading, tides and rotation, Chandler Wobble, atmospheric tides, solar irradiance, geomagnetic tides, tides in wells, tidal triggering, tidal tilt modification, satellite orbit perturbations, tides of Io, binary star systems and tidal interactions of galaxies.

A historic review on the scientific gravity work from 1870 to 1991 in the old Geodetic Institute of Potsdam and the former ZIPE is given in ELSTNER et al. 1997.

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# Sea level and ice sheet variations

R. DIETRICH

## Geodetic research in arctic and antarctic regions

A precise geodetic positioning is an important prerequisite to study ice-ocean-solid earth interactions in polar regions. As a part of the working program of the working group on Geodesy and Geographic Information within the Scientific Committee on Antarctic Research (SCAR) and of the Special Commission 8 of the IAG Germany has contributed to a large extent to the SCAR GPS Epoch Campaigns since 1995 (DIETRICH 1996, DIETRICH et al. 1996b, 1998a, 1998b). In a first step a densification of the ITRF in Antarctica was carried out. This was followed by a determination of crustal deformations, e. g. in the region of the Antarctic Peninsula (DIETRICH et al. 1998a, 1998b).

In Greenland a precise GPS network was set up to investigate ice-induced vertical crustal deformations (DIETRICH et al. 1996a, 1998e).

Gravimetric Earth tide observations were carried out in Greenland and Antarctica in order to study ocean tidal loading effects and thus to improve GPS positioning concerning ocean loading corrections (DIETRICH et al. 1998d, DITTFELD et al. 1998, SCHEINERT et al. 1998).

The geodetic investigation of ice mass dynamics and ice mass balance was concentrated on regional scales in Antarctica. One decade of repeated field observations in Dronning Maud Land revealed areas with a significant negative mass balance (KORTH, DIETRICH 1996, KORTH et al. 1996, KORTH 1998). A combination of surface data and interferometric SAR (ERS-1/ERS-2 tandem mission) could be used to confirm the 1 cm level accuracy for ice surface displacements determined by InSAR (DIETRICH et al. 1999) and to study tidal signals and the grounding line location in the grounding zone area (DIETRICH et al. 1998c, METZIG et al. 1999). The InSAR technique could be applied to monitor parts of the Antarctic ice sheet and glaciers (MÜLLER et al. 1997).

Ice sheet topography could be mapped by satellite radar altimetry from GEOSAT (HEIDLAND 1995) and ERS-1 mission (SIEVERS et al. 1995). Remote sensing data were also one important source for multi disciplinary applications in glaciology (VAUGHAN et al. 1995) and satellite topographic mapping (MANTRIPP et al. 1996).

The validation and improvement of global geoid models in Antarctica was carried out for the Weddell Sea based on satellite altimetry data (SCHÖNE et al. 1996a, SCHÖNE 1997, SCHÖNE, SCHENKE 1997, 1998) and for the region of Schirmacher Oasis using surface gravity observations (KORTH 1998, KORTH et al. 1998).

## Sea level variations, ocean currents and greenhouse effect

Further improvements of the accuracy in the field of satellite altimetry provided excellent possibilities to study the mean sea surface and its temporal variations. A global high resolution mean sea surface model was determined (ANZENHOFER et al. 1996), and investigations how to generate a long-term mean sea surface model including satellite missions of the 80s was carried out (BOSCH 1999).

A refined analysis of ERS-1 altimeter data over 3 years could be applied to generate a time series of global monthly means for the global sea level with an obtained change rate of +2 mm sea level rise per year (ANZENHOFER et al. 1997, 1998).

Regional studies were carried out in the Caribbean to investigate absolute sea surface topography (BOSCH 1998) and in European seas to understand the sea surface variability on low and medium frequencies (FENOGLIO-MARC 1999).

For the South Atlantic region transport estimates could be derived from ERS altimeter data (ROMANEESSEN 1997).

Tide gauge records at the German Baltic Sea coast over 150 years could be analyzed, a variability with a 20...30 years cycle was detected (LIEBSCH 1997).

## Verification of mean sea level variations by combination of observation techniques

Satellite altimeter data of each mission need to be checked by independent observations to monitor the altimeter bias and a possible altimeter drift.

A multi-mission calibration of satellite radar altimeters including ERS-1, ERS-2, TOPEX and POSEIDON was carried out by OSKAM (1999). In the Baltic Sea tide gauge data in combination with GPS could be used to verify TOPEX altimeter data (LIEBSCH, DIETRICH 1998, 1999a, 1999b).

## Studies on the vertical datum

Space geodetic techniques (GPS) and improved geoid models provide excellent possibilities to study the vertical datum realization. GRAFAREND AND ARDALAN (1997) computed the primary geodetic parameter $W_0$ for the Finnish height datum N60.

An analysis of the sea surface determination with respect to several European vertical datum was carried out by FENOGLIO (1996).

The reduction of historical German Baltic tide gauge records into one vertical datum was carried out (LIEBSCH 1997, LIEBSCH et al. 1999).

The combination of GPS height determination, tide gauge observations and geoid models could also be applied to study the vertical datum realization in Antarctica (SCHÖNE et al. 1996b, 1998, IHDE et al. 1997, KORTH 1998).

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# Earth rotation variation and its geodynamic causes

E. GROTEN

Earth rotation studies for the interval 1995-99 are basically summarized in this paragraph according to the following subdivision or scheme

- Nutation and Precession
- Polar Motion
- Tidal Effects
- Ocean and Atmospheric Influences
- Core-effects
- Reductions of Observations
- Theoretical Investigations and Analysis
- Special Observations
- Various other Rotational Effects

The results of related research are, however, presented within the frames of the institutions where the studies have been carried out. In so far this paragraph is basically a compilation of the original reports by institutes whose authors are referred to as far as possible. One of the corner research topics in Germany of the aforementioned interval was the construction of the laser-ring gyro table by the Satellite Center of TU Munich (Prof. SCHNEIDER) and IfAG (now BKG) built in connection with earth rotation studies (by VLBI, GPS, SLR and superconducting gravimetry) at the Fundamental Station Wettzell.

## 1. Polar motion and nutation studies carried out at TU Darmstadt

Polar Motion and Nutation in their longer-period part was investigated by S.M. MOLODENSKY and E. GROTEN (G&M, 1996a,b,c; 1999; M&G 1995a,b, 1996, 1997, 1998a,b,c, 1999) where the influence of the atmosphere, the core-mantle boundary, an elasticity of the mantle, inner and outer core effects were taken into account and related quantitative estimates are given within the ranges of observability.

**High-frequency earth rotation analysis and modelling:**

Since the discrete deterministic modelling of various parts of the short-period spectrum in Earth rotation data did not yet lead to conclusive results and spurious systematic variations in Earth rotation data, such as seasonal effects obviously do exist *(*ARFA-KABOODVAND et al., DGK, 1998), *so* a systematic search on the degree of variability of periods including tidal (diurnal etc.) frequencies appeared useful. The basic problem of such studies lies in the fact of imperfection of eliminating direct tidal effects which induce in the various bands apparent variability of periods which simply reflects imperfection of the tidal model containing nearly tidal frequencies which cannot be exactly taken into account in the data analysis. On the other hand, in the subdiurnal frequency range, mainly oceanic influences could be identified by detecting pronounced frequency modulation or non-linearities.

In the prediction of polar motion for high-precision satellite orbit modelling two-dimensional approaches are basically superior to conventional one-dimensional polar motion approaches as they better take account of correlation between x- and y-components which reflects the physical meaning of the motion of the Earth rotation axis. In view of interruptions of satellite orbit data we consequently used different spectral analysis techniques like Fourier transformation method and Maximum Entropy Method (MEM) in two-dimensional form as reference (with fixed periods) in the non-tidal and tidal bands of the subdiurnal ranges and compared the associated results with the results obtained from two-dimensional Wavelet-analyses. Further information relating to the properties of the Fourier method and MEM for analysing the Earth rotation data and the advantages of using 2D-Wavelet method have been proposed in paper of ARFA-KABOODVAND et al (Studia geophysica & geodaetica, 1998).Consolidate information relating to the ulterior motivations of using the Wavelet transform for analysing the Earth rotation data and some detailed theoretical background of Wavelets as well as their application have been proposed in papers of ARFA-KABOODVAND et al (ZfV, 1998). In all three cases special software-packages had to be prepared. These analyses were mainly based by us on 21-days data sets taken over the aforementioned total data set length of about two years.

The results of the Earth rotation analysis indicate some irregular variations in polar motion and LOD. These may have a common geophysical cause. Also the effective atmospheric angular momentum could be in daily/subdaily frequency band one of the responsible sources for the irregular variations in x- and y-pole coordinates and depends on the epoch of computations. As mentioned before the data contains some systematic contents which could be used for deterministic modelling of polar motion in subdiurnal domain. In the results of 2D-Wavelet transformation of the Earth rotation using a subside factor of 1 to subdaily prograde and daily retrograde period variations were recognisably significant. We notice in daily/subdaily frequency band (within the whole data set) that the retrograde part of the polar motion spectrum is more energetic than the prograde part of it. This indication leads to the fact that the daily oscillations are mainly clockwise and the subdailies are counterclockwise. Additionally a prograde band width of 14 day was ascertainable followed by a 7 days band lack which are generally covered by the retrogrades. Since the tidal forcing of the oceans dominate the rotational variations at periods of one day and less, so we expect the ocean tides as the main exciting force for these phenomena. Furthermore, we discovered within the whole data maxima in prograde and retrograde spectral density, especially in spring and autumn, i.e. rotation data. So, it is 18.06/3/1995-10/4/1995 and 8.96/9/1995-29.75/9/1995 etc. which may be attributed to the seasonal variations in the polar motion. Inserting a higher subside factor (i.e. 4) in the Wavelet analysis allows us to crystallise more information referring to the variation behaviour of Earth interesting to see the dominance of the prograde polar variations in the early spring and whole summer as well as the retrograde polar variations in the whole spring and late summer. Also in the second half of the year some retrograde subdaily variations have been detected. Because of the conciseness and short total length of Earth rotation data, it is not possible to realise any significant yearly coherence between the prograde and retrograde spectra as well as LOD. We also discover some dependencies between the prograde and retrograde spectra in the polar motion (i.e the yearly appearance of pro- and retrogrades in April and September). Finally, we found out some special cases in the polar motion, where both daily prograde and subdaily retrograde periods occur (i.e. May 1995, December 1995, September 1996, December 1996 and March 1997). Since the daily/subdaily variability due to AAM is quite small compared to oceanic tidal effects, so further research is necessary to model, investigate and reduce the Earth rotation data.

It seems necessary to study longer data series before stochastic studies as described here give way and sufficient a priori information to systematic deterministic modelling.

## 2. Earth rotation studies at DGFI (Munich)

### Analysis of nutation data observed by VLBI

The wavelet transform was applied on nutation data observed by VLBI. Before the wavelet analysis was carried out, the IERS correction model (1996 IERS Annual Report, 1997), which contains 25 astronomical terms including an annual variation, had been subtracted from the data. In the complex-valued nutation parameters ($\Delta\epsilon - i\Delta\Psi\sin\epsilon_0$) the retrograde Free Core Nutation (FCN) can be seen clearly around a period of 430 days (SCHMIDT and SCHUH, 1999). The wavelet transformation reveals a significant decrease of energy in the range of the FCN since 1989/1990. From a closer look at the output of the wavelet analysis of the nutation series, it can be seen that not only the energy related to the FCN has changed, but also the period which corresponds to the highest energy in the wavelet spectrum at a particular time has varied in the span from 1984 till 1996. A about modulation period of 4.8 years can be extracted, which was discussed in more detail by SCHUH and HAAS (1998).

### Resonance of the free core nutation in the solid earth tides

In the last three years progress has been achieved in the determination of tidal deformation parameters directly by least squares adjustment of VLBI data. About 800.000 VLBI observables covering a time period of 17 years and measured by the global geodetic VLBI network were used for the most recent global solution. Second degree and third degree Love and Shida numbers of the solid Earth tide model were determined. The results for the different parts of the tidal spectrum (long-period, diurnal, semi-diurnal) were published by HAAS and SCHUH (1996), HAAS et al. (1996), HAAS and SCHUH (1997), SCHUH and HAAS (1997), SCHUH and HAAS (1998). They are slightly different for the various frequency bands, and a clear resonance in the tidal deformation can be seen around the Free Core Nutation [FCN]. In a more general approach, complex Love and Shida numbers are used. This corresponds to a phase lag of the tidal deformation, e.g. due to the inelasticity of the Earth. Imaginary parts of the Love numbers $h_{21}$ and $l_{21}$ were computed for the strongest semidiurnal and diurnal tides. Finally, the complex eigenfrequency of the FCN resonance was determined, with an FCN period of 427 ±21 days in the celestial reference frame and a quality factor Q of 1730 ($1240 < Q < 2840$). This direct determination of Q based on tidal deformations measured by VLBI agrees rather well with superconducting gravimeter measurements but disagrees with former analyses of VLBI nutation data.

Further investigations of geodynamical effects related to the tides using VLBI observations were carried out. HAAS and SCHUH (1998) determined ocean tidal loading parameters for the main geodetic VLBI sites and HAAS et al. (1998) compared different atmospheric loading models with results obtained from VLBI.

### Wavelet analyses of earth rotation parameters

The wavelet analysis has several remarkable advantages compared with the classical Fourier or spectral analysis. It allows the time localization of an unstable quasi-harmonic signal within a given data set (SCHMIDT 1996). Series of the Earth rotation parameters published by the IERS and of atmospheric angular momentum data have been analyzed by SCHMIDT et al. (1997) and by SCHMITZ-HÜBSCH (1998). The analysis of lod (length of day) series yields in the high frequency range periods of 28 days, 14 days down to 5.6 days caused by lunisolar tides and irregular periodic variations between 40 and 100 days. These are mainly excited by zonal winds. For the circumpolar semi-annual variations of lod a strong correlation with El Niño events and with the antarctic current can be seen. The main components of polar motion are the prograde Chandler wobble with a period of about 1.18 years and a prograde annual variation. If the Chandler wobble is subtracted first from the observed polar motion, the wavelet analysis of the residual data shows a significant variation of the amplitude of the annual period. In particular after El Niño events large annual variations of polar motion are found. Additionally, variable periods between 3 and 5 months can be seen in the wavelet spectrum of the short period range (SCHMITZ-HÜBSCH 1998).

The differences between the nutation coefficients observed by VLBI and the best-known astronomical nutation model were investigated, too. The IERS correction model (IERS Annual Report 1995, Paris 1996) which contains 25 astronomical terms including a constant annual variation, had been subtracted first from the data. The wavelet transformation of the nutation data treated in the complex plane ($\Delta\epsilon$- i · $\Delta\Psi$ · sin$\Delta\epsilon_0$) shows an additional nutation component around 430 days which can be referred to the Free Core Nutation (FCN). The decrease of its amplitude since 1990 is clearly revealed by the wavelet analysis (SCHUH and HAAS 1998). When looking closer on the output of the wavelet analysis it can be seen that not only the energy related to the FCN has changed but also the period which corresponds to the highest energy in the wavelet spectrum at a certain time (ridge function) has varied considerably in the span from 1984 till 1997. There is probably a modulation of the FCN period close to 430 days with at least one other non-astronomical nutation term. Such a modulation could be caused for instance by an irregular atmospheric excitation of the annual nutation which is still contained in the residual nutation data.

**First steps towards real-time measurements by VLBI**

Based on the inertial reference system of extra galactic radio sources, VLBI is an extremely precise modern geodetic technique for monitoring the Earth rotation and for the realization of the global reference system. However the costs are relatively high and there is still a delay of one week minimum between the time of observation and the availability of the results. If this gap could be shortened to a few hours this would allow to monitor the Earth rotation parameters quasi in real-time which could be extremely useful, e.g. for the prediction of the Earth rotation parameters. As a first step towards real-time VLBI a direct transmission of the received signals from the radio telescopes to the correlator or to a central computer for further processing was proposed by SCHUH (1995). High bandwidth communication networks using optical fibre or communication satellites will soon allow intra- and intercontinental transmission of signals at some Gbit/sec. In the final data analysis many steps which are carried out manually can be supported by artificial intelligence methods. The concept of an expert system (XPS) for processing Very Long Baseline Interferometry (VLBI) data was presented by SCHUH (1996). It is an intelligent knowledge-based assistant for the MarkIII Data Analysis System (one of the most widely used VLBI software packages) and supports and guides the analysts to make the data analysis faster even if they are less experienced. This XPS is being developed in a research project at DGFI, Munich. The XPS guides and controls the operations done by the analyst and does all necessary checks automatically. It gives detailed explanations to the analyst (decision support system) in particular when he/she has to choose between different options or has to select specific models or parameters. When failures or problems in the process of data analysis have occurred, the XPS advises the analyst how to overcome the problem (diagnostic system). The system contains a flexible and extensible knowledge base. First examples of an automated editing of station log-files showed that the program flow can be considerably accelerated.

## 3. Research activities on earth rotation at the GeoForschungsZentrum Potsdam (GFZ)

Research on earth rotation at the GFZ is focussed on data analysis and the interpretation of geophysical causes of variations of the length of day (LOD) and polar motion (PM).

**ERP products of the IGS analysis center at the GFZ.**

Since the beginning of the IGS in 1993 the global GPS data have been analysed by the international IGS Analysis Center at the GFZ Potsdam. The excellent data distribution (compared to the other space techniques) allowed for a daily resolution in the ERPs from the very beginning. Today a continuous daily series for an interval of 6 years is available.

There are two categories of products, rapid and final ones. The rapid product is based on an optimized set of about 30 well distributed sites and is computed 12 hours after the end of the day. It is the most important input for the Bulletin A. The final product is derived on a weekly basis, four days after the end of the week, and it uses about 60 sites.

During the first years the accuracy for polar motion and the length of day was 0.2 – 0.3 mas and 0.06 ms, respectively. This accuracy is of course strongly connected with the accuracy reached in the realization and maintenance of the terrestrial reference frame. This realization crucially depends on the quality of the GPS stations (data, environment, monumentation) and of the orbit models. On both fields a remarkable improvement could be gained from year to year, so that the ERP accuracy was improved until 1997 by a factor of two.

In May 1997 the LOD determination could be improved on about 0.04 ms by introducing orbital arcs with a length of 3 days, instead of the formerly used 1 day. At the same time GFZ started to submit results for UT1, which are aligned on the first day of each week to Bulletin A. The accuracy within the week is better than 0.1 ms. Additionally, the daily polar motion rates are estimated, here the accuracy level is about 0.2 mas/d.

This already high level was even improved in March 1998 by switching from ITRF94 (with 13 fixed core sites) to ITRF96 (with 74 fixed core sites). This enlargement in the set of core sites stabilized the reference frame realization during the daily analysis.

| | Rapid | | Final | |
|---|---|---|---|---|
| | ITRF94 | ITRF96 | ITRF94 | ITRF96 |
| xp[mas] | ± 0.29 | ± 0.16 | ± 0.11 | ± 0.07 |
| yp[mas] | ± 0.29 | ± 0.14 | ± 0.15 | ± 0.09 |
| LOD[ms] | ± 0.036 | ± 0.031 | ± 0.026 | ± 0.016 |

The largest improvement can be stated for the rapid products, which have now an accuracy of 0.15 mas, which corresponds to the former accuracy of the final products (GENDT et al. 1998 a,b)

**Geophysical causes of variations of the earth's rotation.**

Geophysical processes accompanied by mass redistributions cause variations of polar motion and the length of day. The impact of atmosphere dynamics, ocean dynamics, and core dynamics on these variations are subjects to investigations at the GFZ. Variations of polar motion and the length of day can easy be estimated if sufficient information on the corresponding process is available. This is valid for atmospheric mass redistributions which are sufficiently monitored by meteorological observatories. Seasonal variations of polar motion and the length of day are expected to be mainly excited by atmosphere dynamics.

In (HÖPFNER 1995d-g, 1996a,b) it was studied whether the Atmospheric-Angular-Momentum functions (AAM) published by the IERS can completely explain the annual and semi-annual periods of polar motion. It was found that the non-atmospheric excitation is much larger than expected. For the annual component the influence of the atmosphere is reduced by the non-atmospheric effect, for the semiannual component it is enlarged.

Imbalances in seasonal variations of the earth-atmosphere axial angular momentum budget are re-examined in (HÖPFNER 1995b,c, 1996c-e, 1997a-c, and 1998a-d) on the basis of LOD and AAM series. The seasonal oscillations are separated by filtering from different time series. Their characteristics are illustrated by the temporal variability of the amplitudes, periods, and phases of the annual and semi-annual oscillations. The results derived from different LOD and AAM systems show to which extent the variations reflect systematic differences and significant signals, respectively, which is important for future activities in this field. The imbalances in seasonal variations may be largely eliminated, if the missing impact of wind from the 10-1 hPa is included in the solid earth-atmosphere axial momentum budget. At the achieved level of uncertainty, the earth's axial angular momentum budget for the annual oscillation is most likely closed with the missing wind contribution alone and for the semiannual oscillation with the missing wind contribution and the hydrological contribution, as estimated quantitatively. An excitation source such as the Antarctic Circum-Polar current is not any more negligible on a higher level of certainty.

Long term variations of the length of day and polar motion are generally attributed to geophysical process in the more solid spheres of the earth, particularly core dynamics is said to be a candidate for decade variations of the parameters of earth rotation, but an estimation of the atmospheric excitation function of polar motion and the length of day for the interval of time 1900 – 1989 shows that long term influences of the atmosphere can be expected.

In (JOCHMANN, GREINER-MAI 1996 and GEINER-MAI, JOCHMANN 1998) the studies of long term variations of LOD are focussed on explaining the climate cycles contained in this time series. It was found that the 11 and 22 years cycles are mainly caused by variations of atmospheric circulation, while the remaining decade fluctuations are probably produced by the impact of core mantle coupling. Investigating the variations of polar motion for the period 1900 – 1989 a number of climate cycles could be identified (JOCHMANN 1998b). These cycles were also found in the amplitude modulations of the Chandler-wobble. The source of this modulation is difficult to explain because it needs only a small excitation with respect to the large transfer function in the area of the Chandler wobble. Comparing the amplitude spectra of polar motion with those of the corresponding excitation function it was found that the 11 years period and the 80 years Gleisberg cycle are partly caused by atmospheric mass redistributions. The relations between these cycles and their atmospheric excitation are similar to that of the annual wobble. Considering inner core motion as a possible candidate for exciting decade fluctuations of polar motion it could be proved that the 11, 22, 30, and 80 years cycles are mainly caused by this process. An obtained phase shift between inner core excitation and polar motion supports this result because it corresponds with the Alfven wave velocity in the outer core. This indicates that climate cycles in earth rotation seem to be more related to core dynamics than to atmospheric circulation.

Investigations on magnetic core-mantle coupling were continued using improved data series of variations of the length of day and the geomagnetic field. Variations of LOD were reduced because of atmospheric effects (GREINER-MAI 1995, JOCHMANN and GREINER-MAI 1995,1996; GREINER-MAI and JOCHMANN 1998). Then the coupling model works with an electric conductivity in the lower mantle which is reduced by about 14% towards a more reasonable value. A new LOD data series was constructed using modern and historical data (LIAO and GREINER-MAI 1998) and compared with coupling parameters derived from the spherical harmonic coefficients of the International Geomagnetic Reference Field (IGRF). This shows no essential improvement of the previously obtained results in the interval of decade fluctuations. In the interannual time scale the atmospheric excitation of LOD variations can play an important role. Common periods are found near 4.55, 4.10, 3.57, 2 57, 2.35, and 2.19 years with good consistencies in amplitudes and phases. However, the dominant period of 5.39 years in the observed LOD variations must be mainly caused by other geophysical processes.

Relations between geomagnetic field variations and polar motion were studied, taking into account the hypothesis of inner core motion. According to this hypothesis the figure axis of the oblate inner core coincides with the dipole axis of the geomagnetic field. The motion of the figure axis of the inner core, which is expressed by temporal variations of the dipole axis, causes mass redistributions because of the density difference between the inner and outer core. These mass redistributions influence variations of polar motion and the gravity field. In (GREINER-MAI 1997) the above mentioned hypothesis was checked taking into account a dynamo process simulated by a prescribed electric current system within the electrically conducting outer core. It was found that the assumed coincidence between both axes is given, if the magnitude of the angular velocity of the inner core is sufficiently high and the current system is concentrated in a thin sheet at the outer-inner core boundary.

In (GREINER-MAI et al. 1998) the influence of inner core motion on polar motion and on the gravity field was calculated, using the above mentioned hypothesis and standard density models of the earth. Comparing the obtained theoretical values of polar motion with the observed one, corrected for atmospheric effects, it was found that polar motion variations caused by inner core motion are of the same order of magnitude as the decade variations of polar motion derived from pole coordinates. Calculations of the gravity potential show that the rotation of the inner causes gravity changes detectable by modern satellite missions (see REIGBER et al. 1997 and TAPLEY 1997). The predicted rates of change of the Stokes coefficients for the last 10 years are 10 exp-12 per year for C2m (m= 0,1,2) and S22, 10 exp -11 for S21. If these values are compared with the accuracy of present gravity models (e.g. GRIM4 SCHWINTZER et al. 1997) and with the accuracy of future satellite missions (CHAMP and GRACE) it seems to be possible to check the hypothesis of inner core motion within the next decade.

The influence of ocean tides on polar motion and the length of day were treated in (SEILER and WÜNSCH 1995 and WÜNSCH 1995, 1997). Basing on the Seiler model of ocean tides more complete results for tidal induced periodic changes of Universal Time and polar motion were given. 24 smaller tidal constituents were added to the 10 previously published.

The increasing accuracy of satellite missions allows an improved determination of the gravity field and its temporal variation. In (JOCHMANN 1997b) it was discussed whether the combined use of temporal variations of the gravity and the earth's rotation reduces the ambiguity of inverse solution for identifying global geophysical processes. It could be shown that these type of inverse solution allows to differ between motion and matter terms of the excitation functions of earth rotation without knowledge on the exciting geophysical process.

An example of inverse solution is given in (JOCHMANN 1997a,1998a). Since the annual wobble of polar motion can not be completely explained by atmospheric mass redistributions, inverse solution was used to identify the unknown excitation. As a possible candidate for this excitation the seasonally varying water storage at the continents was chosen, which is related to the temporally varying precipitation. The relation between these two phenomena could be described by a linear relation with two coefficients depending on evapotranspiration and runoff. These coefficients could be assumed to be independent of the geographical position in case of polar motion. This allowed a successful inverse solution.

## 4. Coordinated research into earth rotation

(M. SCHNEIDER, Munich)

Research on Earth Rotation in Germany funded by the Deutsche Forschungsgemeinschaft (DFG) is coordinated since several years as a cooperative effort. Within this research project three round-table discussions of the scientists involved on topics relevant to Earth Rotation, e.g. on measurement and modelling activities and on reference frames (SCHNEIDER, 1999), have been held.

**Measurement activities**

Measuring Earth Rotation using Space Geodetic Techniques (VLBI, GPS, SLR/LLR) is a prime goal of FGS (Forschungsgruppe Satellitengeodäsie). Within FGS the Bundesamt für Kartographie und Geodäsie in Frankfurt (BKG) and the Forschungseinrichtung Satellitengeodäsie of the Technische Universität München (FSG/TUM) are operating the Fundamental Station Wettzell in a series of internationally coordinated programmes.

FGS is considering also the development of new earthbound rotation sensors, e.g. the development of a Ringlaser of very high sensitivity for geodynamical applications as well as for fundamental physics. A prototype of 1m x 1m effective area has successfully been developed in close cooperation with the University of Canterbury in New Zealand to about 0.5-1ppm. This CII ring laser is fully documented in (FRIESCH et al., 1999). Latest results from this laser gyro are regularly shown in the world wide web

(*www.fesg-tu-muenchen.de*).

There is also shown the output from a G0, a 3.5 m x 3.5m ringlaser developed for demonstrating single mode operation being feasible in a large ringlaser. The CII as well as the G0 are being operated in the Cashmere Cavern near Christchurch, New Zealand which provides good environmental conditions. A 4m x 4m ringlaser is now under construction to be installed underground at the Wettzell Station in 2001, a sensitivity of 1ppb or better envisaged.

Publications relevant to these ring laser developments can be found also under

*www.phys.canterbury.ac.nz/~ physges*.

Furthermore FGS is developing in cooperation with the University of Tübingen (FRIESCH et al., 1999) also a rotation sensor using quantized superfluid vortices in helium 3 or 4, These vortices created in an orifice are detected with a Squid device. A review of helium gyroscopes is given in (ESKA, 1999).

**Modelling earth rotation and its determination**

An overview of modelling activities as well as of processing observables from space geodetic techniques is given in (SCHNEIDER, 1999), at far as these are funded through DFG.

Since several years the member institutes of FGS are contributing on a regular basis to the IERS by delivering EOP from the analysis of observables from space geodetic techniques (VLBI. SLR/LLR, GPS). Analysis of LLR data is done using LUNAR, a programme package developed within FESG/TUM. Its theoretical background is documented in (BAUER, 1989; MÜLLER, 1991), the most recent achievements including the results from processing all LLR normal points available since 1969 using LUNAR are given in (REICHHOFF, in print).

FGS together with cooperating institutes has prepared an illustrated booklet on Earth Rotation (SCHNEIDER, 1998).

Concerning the Bundesamt für Kartographie und Geodäsie (BKG), B. RICHTER reports: The SLR Analysis Centre at the Bundesamt für Kartographie und Geodäsie (BKG) submitted the solution EOP(BKG)98L01 to the IERS. This solution was based on observation data of 86 SLR stations from January 1988 to January 1998. The E0Ps were determined for 3-day intervals. For the year 1997, the rms differences between this solution and EOP(IERS)97C01 was about 0.14 mas for the x and y pole coordinates.

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