INTERNATIONAL GEOID COMMISSION (IGeC)

(Commission XII of Section III of IAG)

Activity Report 1991 - 1995

prepared by

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Preface

The International Geoid Commission (IGeC) was formed by the International Association of Geodesy (IAG) at the XIXth General Assembly of the International Union of Geodesy and Geophysics in Vancouver, 1987. It operates as Commission XII of Section III of IAG. From 1987 - 1991 IGeC was presided by R.H. Rapp with C.C. Tscherning and A.H.W. Kearsley as Secretaries. An Executive Committee was established to support the Commission in forming directions. For the time being 41 countries are represented in IGeC.

In the sequel the main activities of the Geoid Commission in general and of geoid related activities in particular are reported.

1. **Establishment of the International Geoid Service (IGeS)**

   After four years of hard work and very tough negotiations F. Sansò succeeded in the foundation of the International Geoid Service (IGeS). IGeS was established at the Politecnico di Milano and became operative on September 1, 1992. IGeS is being sponsored by the Istituto Nazionale di Geofisica of Italy, the Consiglio Nazionale delle Ricerche of Italy, and the Politecnico di Milano. IGeS is presided by F. Sansò; for the time being IGeS has three staff members.

   IGeS has been designed as the working arm of IGeC. In particular, IGeS works as a nonprofit organization for the benefit of the international geoscientific community. Its main duties and goals are as follows:

- Collection of data related to geoid determinations that are not already systematically collected by other agencies or services, making sure that all data sets provided to IGeS are properly documented.
- Collection of available software for geoid determinations, giving room to the wide pluralism of methodologies, and verifying that the software is properly documented and complete with test examples.
- Computation of geoids in exceptional cases, as defined by the Executive Committee (EC) of the IGeC, in support of national and scientific objectives.
- Pursuing both theoretical and practical work towards the merging of regional geoids into larger solutions.
- Distribution of available geoid-related documented data sets and software upon request.
- Organization of courses on special demand for users who would like to acquire the necessary knowledge to perform geoid computations on their own.
- Preparation and distribution of a bi-annual bulletin describing the current activities and the information available at IGeS.
- Pursuing any other task that the EC of the IGeC would assign to it.

In order to start with IGeS has decided to concentrate its activities for the first term on the following topics:

- Collection and testing of global geopotential models and the corresponding software to produce various functionals of the geopotential at prescribed locations.
- Collection and documentation of preprocessing software, including the first statistical tests on data, rejection of outliers, and data gridding.
- To start issuing a bi-annual bulletin providing information on the service.
- Organization of a first technical training course for geoid determinations.
- Participation in some outstanding international research projects related to geoid determination such as ESA's gravity gradiometry mission ARISTOTELES, GEOMED (geoid and SST determination for the Mediterranean based on ESA's ERS-1 altimeter and other geodata), the European gravimetric geoid (conducted by the University of Hannover).
- Establishment of a close cooperation with the Bureau Gravimetrique International (BGI), starting with a pilot project aiming at the collection and homogenization of digital elevation models for Europe for the purpose of geoscientific applications.

Since its foundation IGeS has issued 4 IGeS Bulletins.

2. **First Continental Workshop on "The Geoid in Europe"**, Prague, May 1992

   The First Continental Workshop on the Geoid in Europe was jointly organized by P. Holota and M. Vermeer. It was held in Prague and attended by over 60 participants from various countries.

   The many presentations covered topics such as

   - The present status of the European Geoid
   - Local and national geoid studies
   - The geoid and geophysical research
   - Problems, practical needs and proposals

   The symposium proceedings were published by the Research Institute of Geodesy, Topography and Cartography in Prague, in cooperation with the Sub-Commission for the Geoid in Europe.

3. **Symposium "Gravity and Geoid"**, Joint Symposium of the International Gravity Commission and the International Geoid Commission, Graz, Sep. 11-17, 1994

   The Symposium "Gravity and Geoid" was a joint effort of the International Gravity Commission and the International Geoid Commission. The scientific part of the conference covered 8 topics:

Faller, J. (USA):	Gravity instrumentation
Marson, I. (Italy):	Intercomparison campaigns
Boedecker, G. (Germany):	Standards, networks, data bases, software
Rummel, R. (Germany):	Space and airborne gravity and gradiometry
Holota, P. (Czech Republic):	Geophysical inversion of gravity and geoid
Sansò, F. (Italy):	Altimetry
Sideris, M. (Canada):	International projects and advanced techniques
Vermeer, M. (Finland):	The geoid in Europe

   The conference enjoyed a very strong international attention which is well documented by the participation of 160 scientists plus 20 accompanying persons from 33 countries from all over the world. More than 120 papers (oral and poster) were presented at the conference.

   The papers were subject to a review process and were published in a conference proceedings volume by Springer-Verlag.

   The conference was financially supported by the International Union of Geodesy and Geophysics, the International Association of Geodesy, the International Science Foundation, and the Austrian Ministry for Science and Research.

4. **International School for "The Determination and Use of the Geoid"**, Milano, Oct. 10 - 14, 1994

The first international geoid school was organized by IGeS and held at the Politecnico di Milano in fall 1995. The following five topics were presented as a series of lectures:

Sansò, F. (Italy):	Basic concepts in geodesy and geoid computation
Rapp, R.H. (USA):	Global models of geopotential
Forsberg, R. (Denmark):	Terrain effects in geoid computations
Tscherning, C.C. (Denmark):	Geoid determination by least squares collocation
Sideris, M. (Canada):	Fourier techniques in geoid determination

The school enjoyed a strong international attention of 34 participants from 17 countries. The lectures were supplemented by practical exercises at the computer where the software packages implemented at IGeS could be tested and used extensively. Lecture notes were made available and will be published IGeS.

The great success of this first geoid school made both the organizer and the lecturers consider a replication of this school in the next years.

5. **Foundation of a Sub-Commission for South America**

D. Blitzkow has taken initial steps towards the foundation of a Sub-Commission for South America with the goal to involve representatives of South American countries in geoid determination matters.

6. **Geoid Questionnaire**

M. Sideris and A. Mainville from the University of Calgary and the Canadian Geodetic Survey Department, respectively, had worked out a questionnaire which addresses very important issues related to the use of the geoid and the specific requirements by the user community. The questions and the given answers can be considered very significant for the planning of further activities of the International Geoid Commission + International Geoid Service and for geoid related research and development in each individual member country.

The collected responses from Canada are very interesting and helpful, but in order to obtain a more globally balanced view it was decided to distribute the questionnaire to all member countries of IGeC. Unfortunately the response to that questionnaire was disappointing; no sound statements and/or recommendations can be made at the moment.

7. National geoid activities

Apart from the mammoth task of the geoid determination for Europe, which is being pursued by the Hannover group with W. Torge and H. Denker, and the latest activities by DMA to compute a global high resolution gravity field model, several geoid related activities went on worldwide.

From available progress reports and the submitted national reports the following information can be extracted:

- Geoid determination has become feasible in several well observed countries with a relative accuracy of fractions of 10^{-6} with a resolution of a few kilometers half wavelength.
- GPS/levelling derived geoid heights are used extensively both to control national geoid solutions and to get hold on long wavelength errors which are due to the used global models.
- GPS/levelling derived geoid heights are furthermore used as geoid observations for geoid determination purposes.
- Altimeter derived sea surface heights combined with gravity data are used both for geoid determination in maritime countries and to separate the geoid from the sea surface topography.
- The very successful project GEOMED was completed by a European consortium under the leadership of F. Sansò, and yielded a very accurate geoid for the Mediterranean area based on gravity and altimeter data.
- Very high resolution digital terrain models (100 m or better) are becoming available in various countries, and are being used for data reduction purposes.
- Several countries from the former East-block released their gravity data and made them available to the international scientific community through the International Gravimetric Bureau.
- Spectral domain techniques such as FFT, the Hartley transform and the 1-D FFT technique proved to be extremely powerful and are becoming widely used by the international geodetic community for geoid determination purposes in many countries.
- Several scientific investigations were conducted aiming at a dedicated gravity field mission which is being discussed by ESA and NASA. It was clearly demonstrated by all feasibility studies that a mission with GPS tracking and a satellite gravity gradiometer as key instrument, flown in a low sun-synchronous orbit of a few hundred kilometers altitude over half a year, would deliver a global geoid with an accuracy of better than 10 cm with a resolution in the range of 100 km half wavelength. Such a mission would enable to precisely separate the geoid from the sea surface topography on global scale.

Graz, October 1995 H. Sünkel

International Geoid Commission

National Report for Australia

by

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1. Geoid Determinations

Over the 1991-94 period, AUSLIG has produced two National geoid models using software developed at the University of New South Wales and modified by AUSLIG to run on a PC. AUSGEOID91 was recently superseded by AUSGEOID93, which is based on GRS80, uses the OSU91 geopotential model, and is gridded at a 201 resolution over the continent.

2. Geoid-related Research Projects

(i) An Australian Research Council-funded research project "A new generation gravimetric geoid of Australia to support GPS geodetic applications" was initiated in 1994. This involves collaboration between Will Featherstone, Bill Kearsley and John Gilliland. Work to date has included the transformation of the Australian Gravity Data Base onto GRS'80, and the validation of this data set.

(ii) The use of the AUSGEOID geoid models during GPS-controlled gravity survey was tested in central Western Australia. The AUSGEOID models were shown to deliver height conversion, reliable to within 4cm when compared to local benchmarks. The AUSGEOID models were also tested in South Western Australia along a 85km levelling profile and AUSGEOID93 proved superior and delivered the equivalent of third order levelling precision.

(iii) Other geoid-related research at Curtin concerns the use of the geoid in coordinate transformations in gravimetry and mapping and the effects of kernel modifications in gravimetric geoid determination. The use of digital terrain models in gravity field determination is also under investigation.

(iv) DEM's have been incorporated into the RINT software to improve the estimation of the mean gravity anomaly for the compartments used in the evaluation of the ring integration around the point of computation. Tests in the ACT area, which has the roughest terrain in Australia, indicates an improvement of about 1.5 ppm in the rms in this area of rugged terrain.

(v) This software combines the various elements of height information (tide gauge, conventional levelling, absolute and relative GPS heights, and gravimetric geoid heights) in an optimal solution by Bayesian least-squares. The technique has been used to investigate the integrity of large sub-sets of the Australian Height Datum, and we conclude that this levelling satisfies the broad (3rd order) specifications of the levelling.

(vi) Geoid computations have been concentrated in South Australia using a precise GPS control network in the Flinders Ranges and also in Melbourne. Other research has investigated the optimum use of integration cap-size in quadratures integration of Stokes (Gilliland).

(vii) A comparison of least squares collocation and numerical integration was made in Melbourne. This showed that the two methods agreed closely and AHD heights could be derived from operational GPS with third order precision.

3. GPS-geoid Information

With the advent of the new Geocentric Datum of Australia via the Australian National and Fiducial GPS Networks (ANN and AFN), there are approximately 70 stations evenly spread over the continent, most of which have spirit levelled heights, and can be used to provide a geometric determination of the geoid height. The differences between these estimates and OZGEOID93 N values show an rms of about 50 cm, with regional trends present in the differences reflecting the fact that the AHD is not an equipotential surface.

International Geoid Commission

National Report for Austria

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Austria is in the favoured situation of being able to use the results of a high-precision local geoid determination, which has been finished and published in 1987 (Austrian Geodetic Commission, Ed., 1987).

This solution is based on a set of approximative 700 astro-geodetic deflections of the vertical and a high resolution digital terrain model.

The used algorithms - modified astronomical levelling and least squares collocation/remove, restore - result an inner accuracy of 15 cm / 100 km and 5 cm / 100km respectively.

A Comparison with undulations, produced by combined GPS and spirit levelling, showed a good agreement with an rms of $\pm$ 9 cm (Erker, E.; Sünkel, H., 1990).

Nevertheless, taking into account the impact of GPS and GPS-levelling, the reached accuracy seemed not to be sufficient. Consequently first initiatives for a cm-geoid started in 1992. A national Geoid-Commission was established under the umbrella of the Austrian Geodetic Commission (ÖKIE) to investigate possibilities for the realization of this goal. An additional acceleration was given by the demand of the EUREF-subcommission for high precision height determination in connection with the establishment of 3 D-reference frames in Europe (Erker, E., 1992). For a correspondent continental geoid solution - the European Geoid Project - gravity and height information was sent to the Institut für Erdmessung, Hannover.

The initial phase of the new Austrian geoid determination was characterized by several activities for finding sufficient personal and financial support. The final solution is a cooperation between three sections of the Technical University in Graz, and the Federal Office of Metrology and Surveying in Vienna. Parallel to the logistic preparations data collecting and data screening was the most urgent topic of the last two years. In the final stage (August 1995) the following data sets are available:

– Gravity data:
  32 400 gravity data provided by the Institute of Meteorology and Geophysics of the

University of Vienna, the Institute of Geophysics of the University Leoben, the Austrian Petroleum Industry, the Institute of Geophysics of the University of Clausthal and the Federal Office of Metrology and Surveying in Vienna. A reduction to some 14 000 data using a 2x2 km grid is foreseen.

- Deflections of the vertical:
  683 homogeneously distributed values are available. This dataset is identical with the basic dataset of the 1987 geoid determination (Austrian Geodetic Commission, Ed., 1987).

- GPS data:
  In 1990, 1992 and 1994 three GPS-campaigns have been performed, establishing the Äustrian Geodynamic Reference Frame, AGREF"(Stangl, G., et.al. 1995). These campaigns covered the territories of Austria, Slovenia and Croatia and included 75 Austrian points. Referring to a geocentric system (ETRF 89, WGS 84) the GPS data can be used for an accurate datum definition and an investigation of long wavelength distortions of the geoid in combination with levelled heights.

- Digital terrain model:
  The Federal Office of Metrology and Surveying provides a high resolution photogrammetric digital terrain model for Austria (50 x 50 m). A two-dimensional surface density model is at hand.

- Global Earth models

- Data of neighbouring countries:
  In principle gravity information and terrain models of the neighbouring countries are available. But the quality and the resolution of the data differ in a wide spectrum. However a homogeneous data set can be produced by prediction and interpolation.

The computation is planned to be done by three different methods:

(1) the conventional least squares collocation

(2) the fast collocation

(3) a gravimetric solution by using FFT.

A comprehensive presentation of these methods has been given in (Sünkel, H. et al, 1995).

The three approaches will be computed independently from three different groups, with the goal to check the results of the finally yielding fast collocation method.

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International Geoid Commission

National Report for Belgium

by

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The Royal Observatory of Belgium (ORB) operates a network of four permanent GPS stations at Uccle, Dendergem, Dourbes and Waremme. The main station of Uccle - Observatory belongs to IGS. The four stations are connected to EUREF through the German network.

The National Geographical Institute of Belgium recently achieved a zero-order GPS network of 36 stations (32 in Belgium, 1 in France, 1 in Germany and 2 in the Netherlands) called BEREF. This network was established using the four previous permanent stations and is thus indirectly connected to EUREF. All the 32 Belgian stations are located as closely as possible in the vicinity of the national first order horizontal stations. One of the aims is to determine precise local transformation parameters between WGS84 and the national datum. These stations are levelled in the Belgian datum which is 2.32 meters lower than the Amsterdamsch Peil. We now dispose of a sparse but well distributed set of reference geoidal heights over Belgium.

On another hand, the Centre de Géophysique Interne et de Géodésie Spatiale (CGIGS) attached to the ORB has carefully validated more than 120.000 gravity data over Belgium and the surrounding areas. Gaps are still existing in the Belgian Gravity Data Bank mostly in the Eastern part of the country where no measurement is performed yet, in the Netherlands and the North Sea. Nevertheless, a first attempt to compute a local geoid was made in collaboration with the IGNF (LAREG) at the end of 1994 using the GRAVSOFT package on the rough data. No DTM was available at that time so that we only used heights informations from the gravity stations themselves. The results are very promising showing, after a least-squares adaptation to the GPS derived geoidal heights, a mean adequacy of ± 5 cm with differences reaching 22 cm in South-East Belgium where the gravity coverage is very sparse. Further computations will be performed in the future using a dense DTM and more gravity data to reach the 1 cm level or possibly better.

International Geoid Commission

National Report for Brazil

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South American Gravity Project (SAGP), a project undertaken and coordinated by the Geophysical Exploration Technology (GETECH)- University of Leeds, has been responsible for the collection and compilation of gravity data as well as topographic data in South and Central America. The project compiled 2,297,373 gravity points on land, marine and airborne. All gravity values have been adjusted to IGSN71 by using "Latin American Gravity Standardization Net 1977" (SILAG 77) and "Rede Gravimétrica Fundamental Brasileira" established by Observatório Nacional in Brazil. The anomalies are referred to WGS-84. The data were acquired from the International Gravity Bureau (BGI), Toulouse,France, from Defense Mapping Agency, Saint Louis, from oil companies and many national academic and non-academic organizations in different countries. Topographic and bathymetric data were used to generate a topographic model in a 3' grid and from that a terrain correction grid of 5' has also been derived. Nevertheless, several data gaps still exist and new measurements are needed to accomplish a homogeneous coverage. In Brazil a specific project called Anglo-Brazilian Gravity Project (ABGP) has been designed to infill some of these gaps in the north and west parts of the country. A new effort has been undertaken in the last two years by Escola Politécnica - University of São Paulo (EPUSP). IBGE and GETECH to estimate mean gravity anomaly values and to use them for geoid computations in Brazil and South America. For this purpose a 30'grid of mean free air anomalies have been derived from 5'mean Bouguer anomalies and mean heights. The terrain correction has been added to the free air anomaly. The modified Stokes integral has been applied after the reference field provided by JGM2 has been removed. These activities are related to the Sub-Commission for the Geoid in South America.

International Geoid Commission
National Report for Canada

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Contributions also by

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Distributed model: Since June 1992, a geoid model referred to as the GSD91 model has been distributed to GPS users. It is a file of geoid heights given along a grid with 5 arc minutes spacing. It was computed using fast-fourier transform using a planar Stokes kernel, as well as the gravity and terrain remove-restore techniques. Its computation is described in (Mainville and Veronneau, 1992). It replaced the UNB90 model which was a 10 arc minutes grid. Its computation is described in (Vanicek et al., 1990).

Additional data: Since 1992, a significant amount of gravity data have been collected over the Yukon, Northern B.C. and Alaska. The model is much improved in these areas, by a factor of two to three. New digital elevation model data were added to the geoid model over various regions of the country and this also improves it significantly. It is recognized that the priority to improve the geoid model over Canada is to collect additional and improved elevation model data. A third of Canada located in the hinterlands require improved elevation model of the same quality as in the populated regions.

Model accuracy: GPS users are using the geoid model to establish orthometric heights compatible locally with official orthometric heights. The compatibility is achieved by performing a GPS survey well tied to local vertical control and allowing the geoid model to be corrected at most by a local bias and a tilt. Such compatibility has been demonstrated in many regions of Canada at a level of q1 to q10 cm. Since 1990, 700 benchmarks of the Canadian First-Order levelling network have been measured using GPS. These GPS/levelling-derived geoid heights are spaced by 30 km and cover the most populated region of Canada. The geoid model and its accuracy is validated using that data. The accuracy of the Canadian geoid model GSD91 is believed to be between q10 cm and q100 cm. Its relative accuracy (at 95% confidence level) has been demonstrated at q2 cm over 10 km, q6 cm over 30 km, q16 cm over 1000 km and 4000 km. These estimates however include also errors in the GPS data.

A number of scientific geoid models have been computed and new software have been developed. A geoid and quasigeoid models were computed in the roughest region of Canada that showed both to provide the same relative accuracy, i.e., q7 cm over 900 km compared to GPS/levelling in the valleys of British Columbia (Mainville et al., 1995). Model computation techniques are described in (Mainville et al., 1992 and 1995).

Effect on the geoid of the variation of density in the crust was studied by Martinec (1993) and Martinec et al. (1995a).

There was much development on the "Generalized Stokes' Technique" (Vanicek and Sjöberg, 1991; Vanicek et al., 1992), in combination with "Molodenskij's modification of the integration kernel" used by Vanicek et al. (1986, 1987 and 1990) as well as on the "Stokes-Helmert's scheme" investigated more recently by Vanicek and Martinec (1994). Most theoretical work prepared by Martinec et al. (1993, 1994a, 1994b, 1995a and 1995b) and Vanicek et al. (1991, 1994a and 1994b) was performed to remove approximations used in existing theories, which approximations were acceptable when a 1 metre accurate geoid model was sought but unacceptable for decimetre and centimetre geoid model.

Dr. Sideris and four of his graduate students and one Post Doctoral Fellow worked on geoid-related problems. Optimization of spectral geoid determination methods was studied by Li (1993). It was shown that heterogeneous noisy data and error propagation can be handled by FFT methods (Sideris and Li, 1992; Li and Sideris, 1994) and that clever application of the DFT or the fast Hartley transform (FHT) can further improve the efficiency and the memory requirements of the spectral techniques (Sideris and Li, 1992; Li and Sideris, 1992 and 1995). It was also shown explicitely that FFT methods produce identical results to numerical integration when zero-padding is properly applied (Sideris and Li, 1993). Optimized algorithms for computing the effect of the topography were also developed (Li, 1993). Sideris (1994 and 1995) showed that irregular data and grids with incomplete data can be used with (hybrid) spectral methods.

Direct and indirect effects of the topography on the geoid and on airborne gravity and gradiometry were computed by the 3D FFT method in order to avoid the approximations of the 2D techniques; very promising results have been reported in Peng (1994) and Peng et al. (1995). Improvements of the 2D FFT method on the sphere by using multiple bands of data were given in Forsberg and Sideris (1993). The rigorous 1D FFT method was used to produce a geoid for Canada and part of the US by She (1993). This geoid outperformed all existing geoids, giving absolute accuracy at the level of 5 cm after a datum fit over an area of 1000 km by 500 km, and sub-ppm relative accuracies (Sideris, 1993; Sideris and She, 1995). Various tests of geoids on GPS benchmarks confirmed these accuracy levels (Tziavos et al., 1992; Mainville et al., 1992; Sideris and Teskey, 1993; Tsuei et al. 1994; Mainville et al., 1994; Li et al., 1995) and also showed that the geoid can also be used to check GPS for errors (Sideris et. al., 1992a). Regional geoid determination methods are summarized in Sideris (1992 and 1994) and Schwarz and Sideris (1993). The construction of 3D gravity field models, together with the proper choice of upward and downward continuation models, was studied by Argeseanu (1994) for the purpose of establishing a test field for checking the results of vector airborne gravimetry in rough topography (Sideris et al, 1992b). Finally, satellite altimetry research using GEOSAT, ERS-1 and TOPEX data has commenced (Zhang and Sideris, 1994 and 1995) and is currently focussing on obtaining oceanic geoid and gravity by optimal combination of satellite altimetry and shipborne gravimetry data.

Applications of SEASAT and GEOSAT satellite altimetry have been investigated by Zhang and Blais (1993 and 1994). Zhang (1993) completed a Ph.D. thesis on the recovery of gravity information from satellite altimetry data and associated forward geopotential modeling. One investigation on the combination of Stokes'approach and Molodenskij's truncation method for geoidal computations using orthogonal transforms was carried out (Blais and Zhang, 1993). Further research has also been done on inverse problems (Blais, 1994), multiresolution and wavelet transform applications [Nie, 1994; Blais et al., 1995].

A major emphasis during the reporting period was the development of airborne gravity systems for geodetic and geophysical tasks. Three projects can be distinguished. The first is the development of a GPS-aided stable platform for a scalar gravity system, done in cooperation with Sander Geophysics Ltd. Details are given in Wei et al (1991), Zhang (1993), Czompo (1993, 1994), Czompo and Ferguson (1995), and Zhang et al. (1995). Second, the possibility of using an inertial strapdown system in conjunction with DGPS for vector gravimetry was explored together with Canagrav Research Ltd. The principle of this approach is discussed in Schwarz et al (1992), a detailed error analysis is given in Wei and Schwarz (1994) and results of DGPS acceleration determination are presented in Van Dierendonck et al (1994) and Wei and Schwarz (1995). Third, the use of a high accuracy inertial stable platform system for both scalar and vector gravimetry was tested in cooperation with the Inertial Technology Scientific Center in Moscow, Russia and Canagrav Research Ltd. in Calgary. Results are reported in Salychev et al (1994), Salychev and Voronov (1995), Salychev and Schwarz (1995). They show that minimum wavelengths of about 3 km can be resolved with a standard deviation of about 1mGal. The current state of airborne gravity research and some of the remaining problems are discussed in Schwarz and Wei (1994) and the contributions of this new measurement technique to geoid determination in Schwarz et al (1994) and Li and Schwarz (1995).

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International Geoid Commission

National Report for Croatia

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It must be pointed out at the beginning that the Croatian geodesists and geophysicists have continuously participated in the most General Assemblies of the International Union of Geodesy and Geophysics (IUGG), and that they have also organised very successfully the first international symposium on "Gravity Field Determination and GPS-Positioning in the Alps Adria Area" in Dubrovnik and Hvar, October, 1-7, 1989, (the new symposium was not held any more because of the war events).

In spite of that our geodetic experts got the opportunity to participate actively with their works only in Vienna in 1991 as the representatives of the sovereign Republic of Croatia. As a matter of course, the prominent geodetic experts from Croatia, (Čolić, Bašić and others were immediately or a little bit later selected into some Special Study Groups or even into the Commissions within the frame of IAG. Due to a very broad international recognition of our independent state, at the beginning of 1992 it was finally provided for Croatia to achieve its long wished appointment for the provisionally member of IUGG, whereby the Croatian Academy of Sciences and Arts, Zagreb is an indispensable Adhering Body, but also a representative of a young state in the International Council of Scientific Unions (ICSU), as it has been pointed at in (Čolić 1993a). In this case, as well as in the foundation of the Croatian National Committee for Geodesy and Geophysics, the great support by professor H. Moritz, the president of IUGG, was a decisive one, to compare (Čolić 1993b).

The foundation of the Croatian Geodetic Society (Božićnik 1993) has provided the possibility for our geodesists to be presented in FIG as well, then in ICA etc. On the other hand, the State Geodetic Authorities puts a lot of effort into the promotion of the whole geodetic activity in Croatia, see (Gojčeta 1993), and at the same time it supports the development of the international collaboration through the membership in CERCO and other.

We hope that all these efforts will result in selecting Croatia by the Council to be the full member of the Union in 1995 at the General Assembly in Boulder (USA).

This report presents interesting activities of the Faculty of Geodesy at the University of Zagreb and the published self-supporting papers of Croatian geodetic researchers, as well as the papers realised in collaboration with the colleagues from abroad. Altogether there were 41 investigators from Croatia participating in the researches of interest to IAG in the period between 1991 and 1994, i.e.: 17 doctors, among which there is also the first geodesists ever selected to be the full member of the Croatian Academy of Sciences and Arts, K. Čolić (Solarić et al. 1993), but also 9 masters of sciences and 15 qualified engineers of geodesy, accompanied by the 13 colleagues from abroad as well (Austria, Bosnia and Herzegovina, Czech Republic, Germany, USA, Slovakia and Slovenia).

Actually, a smaller number of Croatian authors deals with geodesy exclusively as geoscientific discipline, but the most of them take it as the engineering and technical one. In spite of that, the majority of papers were published in Croatian, but regularly with an abstract in English, and that is the only Croatian geodetic journal with a remarkable international reputation. In 1991 Frančula et al. made the Bibliography of Relevant Papers published in Geodetski list, Zagreb in the period between 1947 and 1990. However, our authors have been publishing their papers in some well known world geodetic journals, and also not rarely in the proceedings of the eminent IAG Symposiums.

In the period from 1991 till 1994 the Croatian geodesists have made three doctoral thesis: Dr. Petrović, 1991 in Graz, Dr. Kapović, 1993 in Zagreb, Dr. Roić 1994 in Vienna, and a few geodetic master's theses have been submitted to the University in Zagreb.

There was also a book published in 1991 (Bilajbegović et at.) intended for students of geodesy and our experts in the praxis. It was realised through the support of two Austrian colleagues and analyses the problems from the area of the Basic Geodetic Works - Modern methods - GPS. The publication (Čolić 1993d) deserves to be mentioned here, in which the geodetic work of Ruđer Bošković, one of the very few pioneers of geodesy in the world in the 18th century is presented in German. There is also a work by Čolić, 1994 devoted to the historical geodetic topic, i.e. to a famous Croat Gjuro Pilar from the 19th century. The modern geodesy in Croatia, especially in the course of the 20th century, is dealt with in (Lovrić 1994).

In the area of Positioning (IAG Section I), a very few articles of Croatian geodesists deal with the triangulation and levelling problems, while most of them present the modern GPS technology. In the paper (Cigrovski-Detelić 1991), the a priori accuracy for a part of the 2nd order triangulation of the territory network of Croatia is analysed, showing that the existing measurements are inhomogeneous. Of course, the existing 3 spatial points coordinates of the 1st order trigonometric network in Croatia, and in smaller extent in the neighbouring Slovenia, with always good basis originating from the old Austria-Hungary, have been recently tested through GPS measurements.

With regard to the vertical reference systems the initial report has been given in the paper (Bilajbegović et at, 1993b) about the reference of the precise levelling at the territory of the neighbouring and independent countries Croatia, Bosnia and Herzegovina and Slovenia. Immediately after that, the review of works accomplished on the precise levelling only on the territory of the Republic Croatia, also with a special attention to the second precise levelling (II NVT) which was accepted as the basic extension network for the execution of the lower order levelling works were presented at first in (Feil et al, 1993b) and then better in German in (Feil et al. 1993c).

The subject of the papers (Benčić, Lasić 1992 and 1994) is the atmospheric influence on geodetic measurements, and the specific topic of the new meteorological activity in the Republic Croatia is considered in (Benčić et al. 1994). In this respect exactly the work (Solarić et al. 1992) about projecting and extensive works on the establishment of the calibration base Zagreb is very significant. The problems of geodetic measurements accuracy are dealt with in the articles (Šimičić 1992) and (Novaković 1993) and others.

After getting acquainted with Ashtech receiver on the calibration base in Zagreb (Bilajbegović, Solarić M. 1991) the first GPS measurements have been made at the points of the upper part of the 1st order trigonometric network at the border of Croatia and Slovenia, and they are the subject of the paper (Bilajbegović et al. 1992a), and in (Bilajbegović et al. 1993a) the preliminary results for a part of Croatia have been presented. The paper (Bilajbegović et al. 1992b) deals with the application of GPS in the local geodetic networks in urban areas, and the interesting topic of the integration of GPS data into GIS is considered in (Galić 1994), while the curves for the transformation from WGS84 coordinates into the state coordinates system are offered in the paper (Bilajbegović, Podunavac 1994).

Finally, with the support of the German Institut für Angewandte Geodäsie (Frankfurt on Main) a very important step has been realised: together with Croatia, Slovenia participated in the campaign EUREF'94, so the necessary GPS measurements with Trimble 4000 SSE receivers were all very successfully executed at 15 first order trigonometric points (Čolić et al. 1994). Leaning on this campaign, the first series of GPS measurements in the project CRODYN has been realised and presented in the same paper, and that is, at the altogether 15 Slovenian points and 1 gauge, and the two Italian points (one is a gauge Triest) have been leaned on.

Referring to other contributions connected with the positioning, not only in geometric, but also in the physical sense, it should be pointed out that in the Republic Croatia they come from geodetic astronomy (partly associated to the Section III). The problem of automatic time recording in determination of astronomical coordinates is dealt with in the works (Solarić 1991 a, 1993a) and (Solarić, Špoljarić 1993a,b,c), and to mention is also the work (Terzić 1993). The improvements of astronomical azimuth determination are shown in (Solarić 1991b), (Solarić, Špoljarić 1992) and (Solarić et al. 1994). In the last paper the original method of passing from azimuth to the grid azimuth has been suggested, although the components of the vertical deviation are not known. In the paper (Solarić 1993b) all automations that have been developed at the Faculty of Geodesy, University of Zagreb in the last twenty years in geodetic astronomy and surveying are presented.

OSU-Report No.416, (Bašić, Rapp 1992), in which there is an oceanwide prediction of gravity anomalies and sea surface heights using altimeter and bathymetric data, can above all be classified into the area of Advanced Space Techniques, (Section II). But also our works belonging to the IAG problem area of Determination of the Gravity Field (Section III) are obviously more or less related to these important problems. In this research area the Croatian geodesists have given the most valuable contributions, along with the above mentioned GPS technology. They have been made within the frame of the scientific project "Gravity filed in geodesy, geophysics and geodynamics". The preliminary results in the gravity field determination for the territory of Croatia are presented in (Bašić, Čolić 1993). The researchers from the Faculty of Geodesy in Zagreb have also conducted the astrogeodetic networks in the neighbouring Republic Slovenia (Čolić 1992b, 1992c). The entire review of Earth's gravity field investigations in Croatia and Slovenia is given in the work (Čolić et al. 1993a) and the improvement of the astrogeodetic and gravimetric geoid solution for Slovenia and a part of Croatia can be found in (Čolić et al, 1993c, 1993e). Finally, in the work (Čolić et al. 1994a) the last status report on the gravity field determination in Croatia has been submitted in the last four years.

In the area of the satellite altimetry for the purpose of determining gravitation anomalies and the surface of the geoid, a special significant activity has been accomplished by Prof. Bašić in the published works which were made during his postdoctoral stay at Ohio State University, Columbus, USA: (Bašić, Rapp 1992), (Rapp, Bašić 1992). On this occasion the geoid and free-air gravity anomalies were calculated globally, i.e. for all world oceans and bigger seas. After his return to Zagreb, the work (Bašić 1993) was made in which he applies the same methodology on the territory of the Adriatic Sea representing almost the half of the entire territory of the Republic Croatia.

For the XXI General Assembly of IUGG in Boulder 1995, the paper "Gravity Field solution for Croatia CRO95" was reported (authors: T. Bašić, K. Čolić, B. Pribičević and D. Medak) in which the astrogeodetic, gravimetric and altimetric solution of the geoid surface through the application of the data from GPS campaign EUREF 94 is reported about.

Thus, in this report we reach the Section IV (General Theory and Methodology). In the field of the geometrical geodesy one should point out the work (Lapaine 1991) in which the new direct solution for transforming, the Cartesian into the ellipsoide coordinates has been given. Lapaine and Frančula (1992) reviewed the most important results about solving the spherical triangle, the orthodrome, the loxodrome, the isometric latitude, the length of the meridian arc, the area of the ellipsoid surface in researches which have been carried out at the Faculty of Geodesy, University of Zagreb, within the frame of the scientific project Cartography and Geoinformation Systems. The new and very simple definition of the isometric latitude is established on the basis of the relation between the loxodrome and the isometric latitude on the sphere (Lapaine 1993). The efficiency of algorithms for computing the geodetic latitude from the isometric latitude have been investigated and presented (Lapaine, Frančula 1993). In (Lapaine 1994) all possible main geodetic problems along a meridian and along a parallel are specified and the algorithms for their numerical solution are given.

The problems of the functional adjustment models of geodetic measurements are dealt with in (Hečimović 1991) and (Rožić 1994). The comment of the accuracy criteria of geodetic networks is given in (Ivković, Barković 1992). A very interesting and original methodology of applying the criteria of maximum correlation in adjustment, with special contributions exactly to the physical geodesy and geophysics has been brought out by (Petrović 1991), 1993a). The most updated application of GIS in navigation is shown in the work (Car, Frank 1994), which researches the general principles of hierarchical spatial reasoning theory and gives the example of their application to wayfinding in large networks.

The contribution of the Croatian geodesists in the field of Section V (Geodynamics) can by no means be avoided. The review of the first modern determinations of vertical Earth crust movements in the land part of Croatia is given in (Feil et al. 1993), and a more complete presentation in (Feil et al. 1992). Kapović and Narobe (1993) research the efficiency of Hannover model in determination of bench marks movements of the levelling network, while the thesis (Kapović 1993) analyses the temperature effects on the motions and deformations of bridges. In the doctoral thesis (Roić 1994) the observation of 3-D structures with the help of theodolite is primarily elaborated.

The above mentioned method of maximum linear correlation coefficients has been realised as the result of the intention to research and use the connection of geoid surface and the Mohorovičić's discontinuity (Petrović 1993b). After the previous works by the Croatian authors only referring to the area of Dinarides, see also (Petrović 1991), the work (Burda et al. 1991) relating to the area of the Western Carpathians was published. Afterwards, the similarities and differences among three mountain belts (Dinaddes, Eastern Alps and Western Carpathians) are analysed.

The problem of determining the density of surface close masses of the Earth's crust in the part of Croatia and Slovenia is dealt with in the work (Čolić et al. 1992). Determination of the leap in the density at the passing from the Earth's crust and the cover for all three just mentioned mountain chains at the edge of Pannonian basin in the centre of Europe is given in (Petrović, Čolić 1994). The new formula and the mean value of 0.22 gcm^{-3} differing from previous hypothesis were given. This was also reflected in the report (Čolić 1993b). The improved method of modelling the density of the Earth's crust layers is given in (Brkić 1994).

The group for physical geodesy of the Faculty of Geodesy, University of Zagreb (K.Čolić, T. Bašić, B. Pribičević and D. Medak) has prepared for the XXI General Assembly of IUGG the work: "Geodetic-gravimetric method for better modelling of geological structures in the test area of Croatia", which is based on the researches of carbon hydrogen findings for the activities of the oil-company.

We would like to conclude our report by emphasising only three the most important works among those planned for the coming period: a) accomplishment of CROREF'95 (Croatian Reference Frame) leaned on EUREF'94 with almost 40 new GPS points (mainly the first order trigonometric points, and to the smaller extent the second order ones); b) establishment of absolute gravimetric network (up to seven points) and beginning of relative measurements within the scope of the wide network of Croatia; c) the improved model of geoid of subdecimeter accuracy for the whole territory of Croatia based on all possible data sources (deflections of vertical, gravity anomalies, satellite altimetry and topography/bathymetry).

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International Geoid Commission
National Report for the Czech Republic

by

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Workshop in Prague

In 1992 the First continental workshop on the geoid in Europe was held in Prague, organized jointly by the IAG-Subcommission for the Geoid in Europe and the Research Institute of Geodesy, Topography and Cartography, Prague-Zdiby, under the sponsorship of the International Association of Geodesy and the Czechoslovak Committee for Geodesy and Geophysics, see (Holota and Vermeer, 1992), (Holota, 1993a), (Vermeer, 1993a,b,c) and (Ádám, 1992). The oral and poster presentations were grouped in 6 topics:

. Present status of European geoid,

. Local and national geoid studies,

. Problems, practical needs and proposals,

. The geoid and geophysical research,

. Specifications for a precise European reference geoid,

. Theory and methods.

In addition to regular sessions a panel discussion on the specifications for a precise European reference geoid and a business meeting of the IAG-Subcommission for the Geoid in Europe were held on this occasion. The work of both the conveners of the workshop (M. Vermeer and P. Holota) was recognized by the International Geoid Commission explicitly at its meeting in Graz, 1994.

Data Transfer

After the Prague workshop in conjunction with the Joint Symposium of the International Gravity Commission and the International Geoid Commission in Graz mean free and Bouguer anomalies and mean heights in 5'x 7.5' blocks from the Czech Republic territory were transferred to the Bureau Gravimétrique International. Simultaneously, the European Geoid Project and a new geoid solution for Austria were provided with these data.

Geoid Solutions

In the reporting period the different detailed quasigeoid solutions based on heterogeneous data sets were discussed in (Šimek, 1991) and compared for the territory of former Czechoslovakia. Investigations related to the determination of the detailed gravimetric quasigeoid for Czechoslovakia were summarized in (Šimek, 1992). The quasigeoid with the resolution 9 km was determined by means of the combination of Stokes' integral and harmonic expansion using terrestrial gravity data (average density 1 point/2-3 km^2) and harmonic coefficients for three geopotential models (OSU-81, OSU-91A and GEM-10C). Different integration cap radii and different expansion degrees were used.

The accuracy of quasigeoid solutions for Czechoslovakia from the point of view of combination of terrestrial and satellite geodetic measurements was discussed in (Šimek, 1993).

An experiment with the determination of high-resolution quasigeoid for Slovakia using only terrestrial astrogeodetic and gravity data was reported in (Šimek, 1995). The resolution of the corresponding model is 2.25 - 4.5 km and the input data source was represented by an extremely dense set of vertical deflections either observed or computed with the help of gravity data. A special attention was paid to the interpolation error of vertical deflections in the mountainous area.

A new solution of the detailed quasigeoid for the territories of the Czech and the Slovak Republics is based on quasigeoid height differences coming from different sources: observed and computed vertical deflections, terrestrial gravity data, harmonic coefficients, GPS observations and leveling. A parametric least squares adjustment of all data was performed using sparse matrix technique. The resolution in higher than 9 km and the formal accuracy, resulting from the adjustment, is 3.8 cm. (Šimek, 1994a,b). An independent check of accuracy was performed by "pure" GPS solution over the entire territory of the Czech Republic and in selected test localities. A realistic accuracy may be, in general, up to 5 cm for the most part, but for some parts, especially for the border zones, it is somewhat lower (5 - 10 cm).

Further investigations on these topics were discussed in (Dušátko et al., 1993), (Dušátko and Vatrt, 1994) and (Pick, 1994c). For the European territory the results of a gravimetric geoid computation can be found in (Dušátko, 1992). Problems of the GPS accuracy and of its effect in the determination of the European geoid were discussed in (Mervart, 1992).

Conversions and Modernization

In connection with the conversion to the WGS-84 system a proposal was made to modernize the definition of the Bouguer anomaly in the Czech Republic and to simplify the computation of the Bullard term at the same time (Pick, 1993, 1994b,d,e). In addition a process of a systematic completion of geopotential differences was initiated (Beneš et al., 1992).

Mathematical Background

Mathematical methods used for the determination of the (quasi-)geoid and associated with studies of the figure and gravity field of the Earth were essentially based on the theory of boundary-value problems and the central role of the Molodensky problem. Effects of the global flattening of the Earth, of the telluroid's topography and of a refined structure of the boundary condition for the disturbing potential were investigated in (Holota, 1991c,b, 1992, 1993a, 1994a). Especially, an extension of the traditional mathematical apparatus and a construction of an iteration solution were examined in terms of functional analysis. An alternative concept was treated in (Holota, 1991a, 1994b). Here the so-called fixed gravimetric boundary-value problem was discussed. In these contributions the well-known direct (variational) method and the weak solution concept were adapted for applications in unbounded domains as this is typical for geodetic boundary-value problems. The weak solution concept was also essentially used in (Holota, 1994c), where properties of the external and the internal branch of the Earth's gravity potential were discussed in conjunction with the classical notion of the geoid. Some further activities related to geoid problems were reviewed in (Holota, 1995b) and (Holota and Kubáčková, 1994).

The theoretical endeavour was also devoted to regional geoid determination from surface measurements in the case when a reference gravity field is given by a global satellite model up to degree and order twenty at least. The method is based on Stokes-Helmert technique (Martinec, 1991d), (Martinec and Moser, 1992), (Martinec et al., 1993),(Vaniček and Martinec, 1994) with precise evaluations of direct and indirect effects of topography (Martinec and Vaniček , 1994a,b), (Martinec et al., 1994a,b) and a regularization of downward continuation of gravity data (Engels et al., 1993). According to the theoretical background of the approach, the method enables to reach the geoid undulations with the accuracy about 10 cm that was confirmed on the territory of Canada (Martinec, 1993a). Global gravity field modelling problems based on spherical harmonic expansions were discussed in (Martinec, 1991a,b,c).

Geodetic Parameters, the Scale Factor and Satellite Altimetry

Results of a systematic long-term investigations on the gravity field and dynamics of the Earth were published in (Burša and Pěč, 1993). They were used practically as well as methodologically in the determination of the geopotential scale factor from satellite altimetry. In (Burša et al., 1992) the geopotential scale factor $R_0 = GM/W_0$ has been determined on the basis of satellite altimetry as $R_0 = (6363672.5 \pm 0.3)m$ and/or the geopotential value on the geoid $W_0 = (62636256.5 \pm 3)m^2\,s^{-2}$. It has been stated that R_0 and/or W_0 is independent of the tidal distortion of surface $W = W_0$ due to the zero frequency tide, see also (Nesvorný, 1993). In (Burša, 1992) the four primary geodetic parameters defining the geodetic reference system are discussed from the point of view of their physical meaning and current estimation of their actual accuracy. The geopotential scale factor has been treated as the primary geodetic parameter defining the Earth's dimensions. In (Burša and Fialová, 1993) four parameters defining the Earth's triaxial ellipsoid (E) have been derived on the basis of the condition that the gravity potential on E be constant and equal to the actual geopotential value (W_0) on the geoid. The geocentric gravitational constant, the angular velocity of the Earth's rotation, the actual 2nd degree geopotential Stokes parameters and

W_0 are taken to be the primary geodetic constants defining E and its (normal) gravity field.

A Note on Geodynamics

Within the use of Runcorn's hypothesis on the existence of convection flows an attempt was made to deduce from the Earth's gravity field a distribution of forces between the lithosphere and astenosphere (Pick, 1992, 1994a). Finally, the recently published book edited by Vaniček and Christou "Geoid and its Geophysical Interpretations" with a number of important contributions was reviewed in Studia geophysica and geodaetica by Holota (1995).

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International Geoid Commission

National Report for Egypt

by

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After the computation of the ASU93 - Geoid that was presented in Graz last September, the following activities are now been done by our group and other colleagues in Egypt:

(1) All the available gravity data at our disposal were sent to Dr. Kumar at the DMA for the joint GSFC/DMA project for improving the model of the earth's gravitational field.

(2) A DTM for some areas of Egypt is now being prepared using 1: 50 000 and 1 : 100 000 Topographic maps.

(3) We are now trying to increase our gravimetric data bank by collecting all the information (gravity, GPS,...) from the different surveying sources in Egypt and encouraging new observation campaigns especially in the remote zones hoping for the recomputation of a new modified geoid for our country in the near future.

International Geoid Commission

Report of the Subcommission for the Geoid in Europe

by

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Introduction

The initiative to create the Subcommission was taken at the Milan Symposium "Determination of the Geoid; Present and Future" of the International Geoid Commission, June 11-13, 1990. Delegates present recommended me for the office of President, for which I was officially asked on June 22 by Prof. Richard H. Rapp (personal comm.) in his capacity of President of the International Geoid Commission.

The task of the Subcommission, following Rapp, would be one of "coordination and communication. The activity in Europe in geoid determination is growing rapidly. Much work has been done in the past. (...)". This tries to be an account of the extent to which these aims have been achieved.

Geoid computation effort at IfE Hannover

The experience with European geoid determination existing in Hannover (Institut für Erdmessung, University Hannover) at Prof. W. Torge's group, as well as the preparedness of this group to continue and improve on their previous work, was a key factor in making Hannover into an official "computing centre" of the Subcommission.

The computation work at Hannover has been in the able hands of Dr. Heiner Denker. In the course of the preparations, many letters were written to institutes in many European countries, in order to request release to the project of gravimetric and / or topographic data. These activities have been quite successful and the new geoid to be presented here in Boulder is probably based on the most comprehensive gravimetric data set so far.

We include two figures, Figs.1 and 2, displaying the gravimetric data coverage, and the digital terrain model (DTM) coverage, as they are at present and will be included into the new geoid under computation. It may be said that also 1^o resolution block gravity data for Russia will be included in the solution.

The Prague Workshop

As a first major meeting of the Subcommission, the "First Continental Workshop on the Geoid in Europe" was organized in Prague, Czechoslovakia, May 11-14, 1992. The local organization was in the hands of Dr. Petr Holota (Research Institute of Geodesy, Topography and Cartography, Prague) and was very well done. Also the Proceedings, a hefty volume (Holota and Vermeer, eds., 1992) was prepared and printed in-house in Prague.

The meeting was judged by most participants to be successful and a useful forum for discussion on future geoid determination in Europe. A more extensive report in this IAG/IUGG sponsored meeting can be found in Bulletin Géodésique (Vermeer, 1993).

The Graz Symposium

The International Gravity Commission and International Geoid Commission's Joint Symposium "Gravity and Geoid" in Graz, Austria, Sept. 1994, included a session on the Geoid in Europe chaired by the author. Many valuable new papers were presented. Like the Prague Workshop, also this meeting was an important forum for discussing all geoid-related issues in Europe and outside.

The Proceedings, edited by Prof. Hans Sünkel, will be available by the time of the Boulder meeting.

The EGS General Meetings

The EGS XVIII General Assembly in Wiesbaden, May 1993, included a session G3: "The European Geoid Determination". Conveners were Heiner Denker and René Forsberg. Proceedings were published by the Danish National Survey and Cadastre (Forsberg and Denker, eds., 1993).

The EGS General Assembly in Hamburg, April 1995, included the session G4 "Progress in Regional Geoid Determination", which was chaired by the author. A number of significant new papers were presented.

The EUREF Connection

At the recent EUREF meeting held in Finland, the author presented an invited contribution (Vermeer, 1995) on the European geoid project. It is indeed important to maintain (or establish, where necessary) a close collaboration between the three European subcommissions: EULN, EUREF and the Geoid Subcommission, as their objects of study are tightly intertwined.

This was also illustrated by a letter (C. Boucher, personal comm.) received by the author while the Prague Workshop was under preparation, pointing out the need for a clear definition of the reference system used for the European geoid, especially in connection with the use of GPS/levelling points. The same point was re-illustrated by a short verbal exchange after the author's EUREF95 presentation with Prof. H. Seeger of IfAG, which touched upon the same issue.

The WEEGP project

The West-East European Gravity project, a collaborative project involving the University of Leeds (GETECH), the International Gravity Bureau (Toulouse), the Russian Academy of Sciences (Moscow), as well as a number of oil companies and national agencies involved in gravimetry, was aimed at compiling and databasing gravity related data covering all of Europe from the Atlantic to the Urals. The project has successfully completed its task and a number of graphic and electronic products have been recently generated.

Some of the data compiled by WEEGP is already being included in ongoing geoid projects, such as (e.g.) the new Finnish gravimetric geoid.

New global geoid projects

New global geoids, i.e. geopotential models, are under way. One is being computed in the USA as a joint project of Defense Mapping Agency and Ohio State University, to succeed in the now dated WGS-84 geoid model and significantly improve upon the current best, OSU91A. Another one has been promised (for Boulder) by the GeoForschungsZentrum (GFZ) in Potsdam (T. Gruber, personal comm.), as follow-up for the models GFZ93A,B, which are known to suffer from some weaknesses.

These new models will provide the inevitable global reference part of the geopotential for future European (and intra-European) geoid determinations to a better precision than ever before.

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International Geoid Commission

National Report for Finland

by

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1. General

Geoid-related work in Finland takes currently only place at the Finnish Geodetic Institute. There, the home-grown package mgm (mass point geopotential modelling) was continuously further developed and extensively used in global and regional work. It uses regular grids of mass points for representing the geopotential, and it is computationally based on frequency domain techniques such as FFT.

2. Global Geopotential Studies

Finland participated earlier in the CIGAR consortium, studying geopotential recovery from a low flying satellite ARISTOTELES, carrying a gravity gradiometric array in a polar orbit at some 200 km altitude. The consortium was headed by Dr. Georges BALMINO, administrated by CISI Ingeniere, and funded by the European Space Agency. During the report period, Finland participated in the follow-up project CIGAR-III, where especially the potential for GPS tracking on ARISTOTELES was studied.

We also did some work on the geodetic aspects of STEP (Satellite to Test the Equivalence Principle). This satellite would fly in a much higher orbit (450-500 km), but carry a highly accurate (± 0.0001 E) single axis gravity gradiometer, and a geodetic GPS receiver. Also the proposed Finnish micro-satellite (HUTSAT, Helsinki University of Technology Satellite) which could carry a geodetic GPS receiver, was studied from this viewpoint, despite its high orbital height, 800 km.

3. Regional Geoid Studies

M. Ollikainen compared the NKG89 gravimetric geoid of R. Forsberg (Copenhagen) with a GPS/levelling geoid as well as a re-computed astrogeodetic geoid, exposing a warping effect at the Eastern border due to lacking Russian gravimetry. A GPS/levelling study in two small areas in Finland is ongoing.

Working on satellite altimetry in the Baltic Sea, M. Poutanen developed a method ("median filtering") for removing outliers from GEOSAT data. Also some work on altimetric crossover adjustment and using tide gauge derived instantaneous sea level corrections was done. Finland participated in the European Space Agency's AO project "dk2", PI C.C. Tscherning of Denmark is also participating in its follow-up AFRICAR (Altimetry for Research in Climate and Resources). Finland participated in GEOMED (GEOid in the MEDiterranean), an EU-financed project. In this framework, Finland has contributed to the study of tidal modelling and determination and comparison of gravimetric and altimetric geoids.

As a cooperative project a gravimetric geoid of Latvia was computed using 150 land gravity points, 400 sea measurements off the coast, and a manually digitized terrain data base. The global reference model used was OSU86F from Ohio State University. A plane fit (one bias, two tilts) to four GPS/levelling points (EUREF-BAL) was done, yielding an RMS of fit of ± 0.22m. Similarly a gravimetric geoid of Estonia was generated, using 4500 Estonian gravimetric points, as well as the above mentioned Latvian data and the Finnish gravity holdings containing also the sea bottom gravimetry performed in the 1950's by Prof. T. Honkasalo in the Baltic Sea. The global reference model used was GFZ93A from GFZ Potsdam. A bias only fit to fourteen GPS/levelling points, was performed, yielding ± 0.1 m RMS.

International Geoid Commission

National Report for France

by

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With regard to the geoid, the latest important French realisations date back to 1971-1978 and are the works of J.-J. Levallois. New needs, both in the scientific domain (studies on vertical references) and in surveying (levelling by GPS), have given the research a fresh boost. Studies in mind to fulfill a national geoid are jointly carried out within two institutions: the Centre National d'Études Spatiales (CNES), which houses the Bureau Gravimétrique International (BGI), and the Institut Géographique National (IGN), from which the Laboratoire de Recherche en Géodésie (LAREG) is dependent. Since 1991, significant progress was made on methods and software, data collection and validation, and field tests were performed.

Methods and software:

Since 1992, the CNES group (BGI) has been developing a series of software [1], of which the main goal is to convert gravity anomalies, deflections of the vertical or geoid undulations (or geoid gradients) in any of these quantities. Classical integration, FFT with Wiener filtering and collocation are implemented. At IGN (LAREG), classical methods for geoid determination (collocation, integrated geodesy, Stokes integration) and existing software (OPERA, GRAVSOFT) have been tested ([3],[4]). A new software for fast integration of gravity anomalies and terrain correction has been completed [5]. New methods and software to fit a gravimetric geoid to a set of levelled GPS points are also developed [6].

Data collection and validation:

IGN completed a new digital terrain model over France [2], aiming at terrain correction computation. BGI carried out the validation of gravity data of France and bordering Countries using the DIVA software [8]. Heights of the point gravity measurements in the data base were compared with those issued from the digital terrain model. TOPEX and ERS1 data were also processed in order to overcome the lack of gravity data at sea. IGN is achieving a new geodetic network [9] comprising about 1000 GPS levelled points which will be used for validation and determination of the national geoid. About 500 points have already been measured.

Field tests:

A dense test network with 63 levelled GPS points was established in south of France [4], allowing to compare geoid models derived from gravity data with GPS and orthometric heights. A precision of 3 cm was achieved.

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International Geoid Commission

National Report for the Federal Republic of Germany

by

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1. Global Gravity Field Models and Modeling Techniques

The German group at GeoForschungsZentrum Potsdam (GFZ) and the French group at CNES/GRGS, Toulouse, cooperate since many years in the generation of global models of the Earth's gravitational potential based upon observations of satellite orbit perturbations.

The latest series of models that were developed at GFZ and CNES/GRGS is named GRIM4 (Schwintzer et al. 1991, 1992, 1993b, Reigber et al. 1993). In a first step satellite-only gravity field models were derived from optical, laser and doppler tracking data collected from some 30 satellites. These models were then augmented through the incorporation of GEOSAT altimeter data, satellite-to-satellite tracking data from GPS-TOPEX/Poseidon as well as single ERS-1 and mixed ERS-1/TOPEX crossover differences (Schwintzer 1994a).

The combined processing of two weeks worth of GEOSAT doppler tracking data and satellite altimeter data allowed a simultaneous estimation of the gravitational potential (spatial resolution approx. 600 km) and the very long wavelength features of the stationary sea surface topography (spatial resolution approx. 4000 km). The resulting sea surface topography model can easily be transformed into geostrophic ocean currents, representing an average over the two week data period during December 1986. The solution based upon satellite tracking data, satellite altimeter data and surface gravity data is called GRIM4-C3T (Bode et al. 1993, Schwintzer et al. 1994b).

Since the launch of TOPEX/Poseidon in 1992 with its onboard GPS receiver high-low satellite-to-satellite tracking data are available from the full constellation of 18 GPS satellites, providing for the first time a dense and homogeneous series of orbit information for a low flying satellite. Using GPS carrier phase and pseudo-range observations the orbit of TOPEX/Poseidon can be recovered in a fully dynamic orbit determination process (GFZ EPOS S/W package) with an accuracy of 3 cm in radial direction and 10 cm in the other components over an arc length of 2 days (Schwintzer et al. 1994b). In spite of the relatively large altitude of the satellite (approx. 1500 km) global gravity field modeling benefits from this new kind of continuous tracking. Data from one complete orbit repeat cycle of 10 days have been added to the GRIM normal equations. The most recent global gravity field solution based upon satellite tracking data and crossover differences is called CRIM4-S4P (Schwintzer et al. 1994b).

At the German Processing and Archiving Center (D-PAF) at GFZ satellite altimeter data from ERS-1 are routinely used to generate geophysical products. Quick-look ocean products and quick-look sea surface height models are generated with a delay of 2 weeks from fast delivery data, D-PAF preliminary orbit and actual meteorological data. Precise altimeter data products (OPRO2) from F-PAF are used to generate short period and stationary sea surface height models, sea surface topography and ocean geoid models (Bosch and Gruber 1991, Anzenhofer and Gruber 1995, Gruber et al. 1994). Quality estimates for these models are provided in terms of internal error estimates and external comparisons with other models. Also a first global mean sea surface model based on the quick-look ocean products was computed for nearly the complete first 168 day repeat cycle of ERS-1 (Gruber et al. 1994). For this ERS-1 mission phase, altimeter data with a spatial resolution of about 16 km at the equator are available, yielding details of the ocean surface which could never be identified before.

The satellite-based gravity field models developed at GFZ and CNES/GRGS (complete to degree and order 50) were combined with high resolution (301 x 301 data) surface gravity and satellite altimeter data from ERS-1 yielding a high resolution global gravity field model complete to degree and order 360 (corresponds to a resolution of 50 km). In this solution surface gravity data were corrected for topographic and atmospheric effects. The mean sea surface based on nearly one year of ERS-1 fast delivery altimeter data from the 35-day repeat cycle (starting in April 1992) was corrected for the sea surface topography as well as permanent tidal effects before being used in the model development (Gruber and Anzenhofer, 1993). Each data set was accumulated into a normal equation system by a least squares harmonic analysis. In this technique, if the input data set has a global coverage and uncorrelated block means with longitude independent weights along each parallel, the normals show a block diagonal structure with no correlations between the C and S coefficients and coefficients of different orders. The quality of the new model was assessed by internal error estimates as well as by comparisons with other high resolution geoid models (Gruber and Bosch 1993, Gruber and Anzenhofer 1993).

Alternative geopotential representations for satellite orbit calculations were studied by Klees and Heck (1992) with emphasis on the CPU time needed on scalar and vector computers. Several representations of the gravitational potential, namely the classical spherical harmonics, the single layer and the point masses, were investigated regarding numerical expenditure, stability and CPU time. In their implementation the spherical harmonic synthesis performed best in terms of CPU time.

The solution and linearization of the geodetic boundary value problems (GBVP) was investigated in detail by Heck (1991). Three types of GBVP were studied, namely the fixed problem involving the assumption of a completely known boundary surface, and the vectorial and scalar formulations of the free GBVP where either the spatial or the vertical components of the boundary position vector are unknown. The originally non-linear problems are linearized with emphasis on the approximations involved.

Grafarend et al. (1991) discuss the geoid and its computation from the gravimetric boundary value problem, focusing on the fact that the geoid is partially in the interior of the Earth where Poisson's equation has to be solved.

The use of Helmert's 2nd method of condensation for geoid and quasigeoid computations was investigated by Heck (1993). All necessary formulas are revised in order to solve the confusion and controversial discussion in the geodetic literature during the past few years, resulting partly from a wrong interpretation of formulas and partly from an improper application of binomial series in the respective integral formulas.

An overall synopsis of the state of the art of satellite geodesy with particular emphasis on recent developments in this field is given in the textbook by Seeber (1993). An introduction to the entire field of geodesy is given in the textbook by Torge (1991).

2. Local Gravity Field Models and Modeling Techniques

Regional geoid resp. quasigeoid models are nowadays required with cm-accuracy over distances up to a few 1000 km in order to meet the demands of geodesy, geophysics, oceanography, and engineering. Especially the combination of GPS heighting with classical leveling is one of the primary drivers for precise geoid/quasigeoid calculations.

The IAG International Geoid Commission therefore decided at its meeting in Milan, 1990, to establish a Subcommission for Europe, which then again asked the Institut für Erdmessung (IfE), University of Hannover, to develop an improved European geoid model. Since the initiation of the project in 1990, IfE has reported about its work at international symposiums in Vienna (Denker and Torge 1991, Torge and Denker 1991), Prague (Denker and Torge 1992), Wiesbaden (Denker et al. 1993a), Beijing (Denker et al. 1993b), and Graz (Denker et al. 1994). Furthermore, results from the geoid project are discussed in Denker and Torge (1993a and 1993b), Torge (1992, 1993a, 1993b), as well as in Denker (1995). A final report on the project will be given at the coming IUGG General Assembly in Boulder, 1995.

In the IfE gravity field modeling effort for Europe the primary interest was in the calculation of height anomalies resp. quasigeoid undulations with the advantage that only gravity field data observed at the Earth's surface and in its exterior enter into the calculations. The basic gravity field modeling strategy at IfE is based on the remove-restore technique. In this procedure the original data are reduced for the effect of a high-degree spherical harmonic model and a digital terrain/density model before applying the modeling techniques, and finally these effects are added back to the prediction results. At present, the main emphasis is put on the calculation of a gravimetric quasigeoid model based on point and mean gravity anomalies, a global geopotential model and a digital terrain model, while GPS/leveling data and other data may be included later on. Due to the large amount of data, FFT was used for the field transformation from residual gravity to height anomalies. The first solutions done at IfE were based on the planar Stokes' formula that was evaluated by 2D FFT in connection with the zero-padding technique. However, these procedures require rectangular grids and therefore neglect the convergence of the meridians, being significant for computation areas as large as Europe. Therefore, in the latest computations carried out at IfE (Denker et al. 1994) it was decided to use the 1D FFT technique suggested by the Delft group (Haagmans et al. 1993), which permits an exact evaluation of any kind of convolution integral on the sphere (same result as with numerical integration) and which is less demanding in terms of computer memory (can run on a PC or workstation). To further speed up the computations, the program developed at IfE uses internally a detailed/ coarse grid approach (see Denker et al. 1994). Moreover, in addition to Stokes' integral, also the spectral combination technique was applied in the latest calculations (see Denker et al. 1994). This permitted the derivation of error estimates for the results and a better control of the signal parts taken from the global geopotential model and the terrestrial gravity data, respectively. The main motivation for using the spectral combination method was originating from the evaluation of the preliminary quasigeoid models with GPS/ levelling and satellite altimeter data. In these comparisons large distortions of the older solutions were found (strong tilts with a magnitude of several meters over the entire computation area), which are due to long wavelength discrepancies between the terrestrial gravity data and the global model used.

A fundamental aspect of the project is the gravity field data base. At first, the existing IfE gravity field data base was extended by the gravity data from Bureau Gravimetrique International (BGI), Toulouse, and, in addition, a number of national agencies were approached to release their gravity and terrain data. These efforts were very fruitful as to date some 70 new land and sea gravity data sources and some 20 terrain data sources were made available. The IfE data base comprises about 1,5 million gravity data and about 650 million topographical data (status Sept. 1994). However, at the moment (begin of 1995) the gravity data coverage is still inadequate for the area of the former Soviet Union, Bulgaria, and some marine areas. Therefore, it was decided to use a 1 deg x 1 deg gravity data set for the area of the former Soviet Union and altimetrically derived gravity anomalies for marine areas with insufficient data coverage (see Denker et al. 1994). Prior to utilizing these data in the quasigeoid calculation, a transformation into a common reference system was carried out, and a thorough data validation was performed using interactive and batch procedures developed at IfE. Unrealistic gravity values were excluded from the quasigeoid calculation, while erroneous topography data were replaced by interpolated or apparently correct values. Finally, areas without high resolution terrain data were allocated values from the global model ETOPO5.

In 1994 six new quasigeoid solutions for Europe were computed at IfE based on Stokes' formula and the spectral combination technique. The spherical harmonic model OSU91A was used for the long wavelength components, while the residual terrain model reduction (RTM) technique was used for the modeling of the short wavelength structures. The solutions were done for the area 25 N-75 N and 35 W-67,4 E using a grid size of 1.01 by 1.51. This yields 3,000 x 4,096 = 12,288,000 grid points. The evaluation of the computed quasigeoid models was done by different GPS/leveling data sets as well as by satellite altimeter data from the TOPEX/Poseidon mission. In these comparisons the spectral combination solutions turned out to be superior to the Stokes solutions. For areas with a good coverage and accuracy of the input data, the accuracy of the best solution is estimated as $\pm 1 ... 5$ cm over 10 to a few 100 km distance, and $\pm 5 ... 20$ cm over a few 1000 km distance, respectively. Problems that need to be further studied concern long wavelength errors of the global gravity models and the terrestrial gravity data. Furthermore, some data gaps still exist, leading to a degraded accuracy of the quasigeoid models in these regions.

The fast collocation procedure was investigated for continental-scale geoid/quasigeoid calculations in a cooperation of the Milan group (Italy) and IfE (Barzaghi et al. 1993). However, due to computer restrictions the test could only be carried out for a thinned data set covering the central part of Europe. The fast collocation and the FFT methods proved to be practically equivalent in this test (± 5 cm std.dev. of the differences with the largest values located near the boundaries). However, the two approaches still differ in terms of CPU time, with the FFT approach being much faster. The comparisons between the fast collocation and FFT techniques showed a periodic pattern with a main wavelength as wide as the computation area, which is due to the different handling of the long wavelength field components in the two methods.

With the experience obtained within the European Geoid Project, geoid/ quasigeoid calculations were also carried out at IfE for other regions in the world resp. special solutions were done for subareas of Europe. This lead to special investigations for Hungary (Ad m and Denker 1991, Adam et al. 1994), Poland (Lyszkowicz and Denker 1994), South America (Torge and Behrend 1993), the North and Baltic Sea (connection of the tide gauge Helgoland with cm-accuracy to the mainland; Goldan et al. 1994, Torge et al. 1995), and entire Germany (Torge et al. 1991), with the latter computation being done in cooperation with the Institut fü Angewandte Geodäsie (IfAG), Frankfurt/Leipzig.

An overview on theoretical and practical aspects of height determination with GPS, leveling, and gravity field data is given in Denker (1991 and 1995), Forsberg and Denker (1993), as well as in Grote et al. (1995). The studies described in Denker (1991 and 1995) and Grote et al. (1995) refer in part to the special situation existing in Germany. Further on, the topic of height and gravity field determination is also covered in the textbooks by Torge (1991) and Seeber (1993).

A thorough study of FFT methods in gravity field modeling was carried out by Tziavos (1993) during his stay at IfE as a Humboldt fellow. A detailed review of the FFT-based formulas is presented for terrain effect and geoid modeling, and improvements and alternatives are proposed for existing techniques. Regarding terrain effect computations, new FFT-based formulas are derived for non-constant density values. Emphasis is put on the use of discrete and analytical spectra of the kernel functions, the treatment of FFT artifacts by zero-padding and filtering/windowing techniques, spherical and planar approximations, and the use of the Fast Hartley Transform. The study by Tziavos (1993) contains all the necessary formulas as well as practical results using data from test areas in Europe and Canada.

A study on the combination of heterogeneous gravity field data sets (gravity anomalies, deflections of the vertical, GPS/leveling data, global geopotential model, terrain data) was carried out in northern Germany (Grote 1993a and 1993b). In this test area, a dense set of gravity stations (2 ... 5 km distance, ± 0.3 mgal) and vertical deflection stations (1 ... 20 km distance, ± 0.511, observed mainly with the transportable zenith camera developed at IfE) is available. In addition, a special GPS campaign, comprising 53 stations with interstation distances of about 50 km, was carried out. The accuracy of the GPS heights was estimated from comparisons of the daily and final solutions as well as from comparisons with leveling and gravity field data, yielding in an error estimate of $\pm 0.01...0.02$ M. A high resolution digital terrain model with a block size of 30 m was utilized as well. However, test computations with different block sizes showed that in areas with a moderately varying topography a resolution of about 200 m is sufficient for quasigeoid computations with cm-accuracy (or even better). Test computations with least squares collocation and integral formulas in an area of about 90 km by 120 km (covering the Harz mountains) showed an agreement between the gravimetric solutions and GPS/leveling data of ± 0.005 M. This is significant improvement as compared to the existing quasigeoid model for Germany developed at IfE in 1989 (± 0.020 m), but this was to be expected due to the use of more detailed gravity and terrain data. Remarkable is also the agreement between the gravimetric solutions and the astrogeodetic solutions for the Harz region of ± 0.016 m) (distance between the vertical deflection stations 1...5 km). Investigations with the fast collocation technique showed a good agreement with FFT and standard collocation results.

The determination of orthometric heights through a combination of astrogeodetic leveling with an integrated CCD camera and D-GPS system was investigated by Eissfeller and Hein (1994). In their system study they discuss the practical implementation of such a system and the accuracy requirements.

Strategies for the combination of GPS heights with geometric and trigonometric leveling as well as atronomical azimuth and position data are discussed in Heister et al. (1991) and Schödlbauer (1991 and 1993). The main goal of their work is the application to engineering projects. Practical results are given for tunneling control networks, bridge construction projects and local geodetic test networks (Schödlbauer et al. 1992a, 1992b and 1993).

The Institut für Angewandte Geodäsie (IFAG) and the state survey agencies of the federal states of Germany are cooperating in order to realize a GPS/leveling reference network (Ihde 1994). The existing GPS reference network DREF91 is used as a basis for the new network comprising about 400 stations. All stations will be connected to the German 1st order leveling network (DHHN92) using normal heights as the basic height system. The major purpose of this network is to strengthen a gravimetric geoid calculation for the area. The problem of geodetic reference systems in eastern Europe with respect to heights and geoid calculations is described in Ihde (1993).

Furthermore the IFAG is also working on a geoid calculation in the Filchner-Ronne-Schelfeis area in Antarctica within the frame of a project named "Exploitation of satellite radar altimetry for monitoring climate change in Antarctica". Observed gravity and height anomalies inferred from the difference of GPS heights and trigonometric leveling are used together with topography and ice models as well as a global geopotential model (Ihde 1995).

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International Geoid Commission

National Report for Greece

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1. Geoid - Sea Surface Topography

The activities concerning the geoid determination for the last four years have been concentrated on the precise gravimetric geoid determination in sea areas surrounding Greece and mainly in the Mediterranean Sea. Extended regional geoid computations have been performed in the above mentioned areas using Least Squares Collocation (LSC) as well as transform techniques (like FFT and Hartley transform). Besides the precise gravimetric geoid determination, the exploitation of the recently available good quality altimeter data from ERS-1/ERM and TOPEX/POSEIDON missions resulted in the precise determination of the sea surface heights. From the combination of the gravimetric and altimetric geoid in the Mediterranean a first approximation of the Sea Surface Topography (SST) was performed. Concerning the continental area of Greece the gravimetric geoid referred to WGS84 has been computed by the Hellenic Military Geographical Service.

2. Theoretical studies and software developments

The transform techniques like FFT competing the LSC have been further developed by using the Hartley transform. In this way the advantages are saving in computer memory and computational time. The relevant software developed includes terrain correction and geoid height computations. The results derived by the transform techniques agree very well with those obtained by numerical integration and stochastic methods.

3. Simulation studies

Extended simulation studies have been performed to investigate the regional recovery of the geoid and the gravity anomalies from Satellite Gravity Gradiometer (SGG) and gravity vector data derived from e.g. satellite-to-satellite tracking (SST). The achievable precision is of interest in connection with the planning a satellite gravity gradiometer mission.

4. Other related studies

In the frame of the geoid related activities several other studies like validation and refinements of the data have been carried out. The validation of the global DTMs like ETOPO5U have been done taking advantage of the precise local DTM's using a new method. Also the validation of the available tidal models for the Mediterranean gave interesting results concerning the possibilities for a cm geoid in the Mediterranean sea.

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International Geoid Commission

National Report for Hungary

by

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In the period of 1991-1995 the European Geoid Project was going on for the determination of a Precise European Reference Geoid. In Hungary we were strongly interested in the success of these efforts for a new European quasigeoid solution improved in spatial resolution and accuracy. Therefore, for the purpose of computing an improved European quasigeoid, the interpolated Bouguer anomalies on a 1.5'x 2.5'grid (appr. 2.7 km x 3 km) and mean elevations in 500 m blocks for the entire area of Hungary have been handed over by the Institute of Geodesy, Cartography and Remote Sensing (FÖMI) to the computing centre of the European Geoid Project, Institut für Erdmessung, Universität Hannover (Ádám et al.,1994). The mean Bouguer gravity anomalies are based on a collection of point gravity data compiled at the Eötvös Lorand Geophysical Institute of Hungary (ELGI). The data interpolated by ELGI was released to the FÖMI. The set of mean elevations has been purchased by FÖMI from the "Agoston Toth" Mapping Institute of the Hungarian Army (MHTATI), where the data were originally prepared. For an independent accuracy control of the European quasigeoid solution, geometrically (GPS/levelling) derived quasigeoid-ellipsoid separations have also been provided. The GPS station coordinates are based on the EUREF points of Hungary.

In exchange the resulting geoid solution for the area of Hungary will be provided (Ádám et al.,1994). This geoid surface will be very important for a check of the individual local quasigeoid solutions determined by the Hungarian institutions.

Six Hungarian research institutions finished a common basic research project on "Global and Local Geoid Determinations" supported by the Hungarian National Research Found (OTKA). The main results of these activities of the research team are summarized in an issue edited by Völgyesi (1992).

The first solutions of the detailed, digital gravimetric quasigeoid for Hungary were completed in 1991. In 1993 a new geoid project was started in order to improve the previous solutions using more reliable gravimetric data (appr. 250 000 measurements in Hungary) and including GPS/levelling data for further improving the performance of the geoid (GPS-gravimetric solution) (Kenyeres, 1993a,b). In this new geoid project, the GPS coordinates (based on the EUREF-89) will be a basic observables.

The computation of the new Hungarian geoid solutions are being performed. Actually, a more precise and complete computation of the national geoid is the basic target in order to reach a more correct and reliable utilization of GPS-techniques (e.g. for GPS/levelling).

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International Geoid Commission

National Report for India

by

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1. Introduction:

The history of geoid determination in India is reasonably very old. The astrogeodetic geoid studies have been carried out in India since 1922 and charts have been published in annual Geodetic Reports of Survey of India, from time to time. In 1924 the International Spheroid was adopted by the International Union of Geodesy and Geophysics and in 1927 it was taken as a reference spheroid in India, defining its geodetic datum in a more or less arbitrary manner, on local considerations only. The deflection components at Kalianpur, the initial point of the Indian datum, had been computed earlier in terms of International Spheroid in 1940 vide Gulatee (1940) and in 1967.

Though, the computations for geoid in India up to 1967 was based on limited amount of surface gravity data available within the Indian sub-continent but later on the same was computed by utilising the sufficient amount of gravity data generated by Survey of India. In addition, the gravity data over the Indian Ocean and outside the Indian sub-continent was also utilised to determine the geoid as accurately as possible. As such, the efforts in connection with geoid studies in Survey of India are still continued with a view to achieve an accuracy of few centimetres in geoid determination in near future.

2. Status of Geoid Studies in Survey of India:

(a) Astrogeodetic Geoid

- (i) The process for the computations of astrogeodetic geoid in India is continued since 1922.
- (ii) Deflection of the vertical at Kalianpur (the origin of Indian datum) in terms of Everest Spheroid was determined vide Gulatee (1955) while the geoidal undulations in terms of International Spheroid 1924 was computed vide Bhattacharjee (1973) by utilising the astrogeodetic data.

(iii) The astrogeodetic geoid in India separately on International and Everest Spheroids based on astronomical data observed by Survey of India upto 1978, have been computed and published in the Bulletin Géodésique, the journals of I.A.G.

(b) Gravimetric Geoid:

(i) Bhattacharjee (1967) has determined geoidal prameters at Kalianpur H.S. in terms of International Spheroid by utilising the limited amount of gravity data within the Indian Sub-continent.

(ii) Khosla, Arur and Bains (1979) have determined the geoidal parameters at Kalianpur H.S. in terms of International Spheroid while Bhattacharjee (1980) has determined it on GRS 1967.

(iii) The gravimetric Geoid in India on International Spheroid was computed by Survey of India (Khosla, Arur and Bains, 1979) while it was computed on GRS 1967 by Bhattacharjee (1980).

The internal consistency of values of undulation at Kalianpur is of the order of ± 0.5 metre and the same for the deflection components at the point is of the order of 10.2".

An accuracy of about 2 metres appears to have been achieved in the determination of Geoid in India.

3. Sources of Data:

(i) The astronomical data entirely observed by Survey of India has been utilised for astro-geodetic Geoid studies in India from time to time.

(ii) 5^ox 5^o and 1^ox 1^o mean free-air anomalies supplied by B.G.I. in 1974 (for areas outside the Indian sub-continent).

(iii) 1^ox 1^o mean free-air anomalies of the Indian Ocean, published by Kahle and Talwani (1973).

(iv) 1^ox 1^o mean free-air anomalies published by DMA (1973). There anomalies were available in GRS 1967 (for areas outside the Indian sub-continent).

(v) Average free-air anomalies near Kalianpur of 5'x 5'blocks computed from Survey of India data using International Gravity Formular. (VI) 1^ox 1^o mean free-air anomalies on GRS 1967, computed from Survey of India Data (over the Indian sub-continent).

4. Future Programmes:

(a) Astronomical Observations for Geoid Undulations

(i) To te-observe the weak sections of geoidal circuits.

(ii) The observations of astro-latitudes and longitudes at those points where only astro-latitudes had been observed in the past.

(iii) To have more astro-observations in areas where there are large gaps.

(b) Gravimetric Undulations and Deflections:

(i) Accurate determination of deflection of the vertical of more stations in India.

(ii) Preparation of gravimetric geoid chart with respect to GRS-67, both by surface data alone and surface data in combination with potential co-efficients.

International Geoid Commission

National Report for Israel

by

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1. Ad hoc application of Rapp's 91'A model (built in all GPS-modules) to compute (Global) Undulation values in selected points.

2. Experiments in the determination the deflection of the vertical from trigonometric levelling and GPS observations. (Reported on ION GPS-94).

3. Pilot project (600 sq.km area) - to implement the trigonometric levelling to compute accurate (subdecimeter) Geoid Undulation map - utilizing DTM and Gravity DATA and gravimetric model.

   70-odd points observed by GPS - 450-odd km accurate trigonometric levelling Data to be processed - software finalized recommendation for implementation will be done during 1995.

   The object to allow quick, easy, accurate transformation from GPS elevation to orthometric heights.

International Geoid Commission

National Report for Italy

by

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The main activity on geoid estimation in Italy in the present period is a new computation of the geoid which has been undertaken by the International Geoid Service by a classical remove-restore technique, exploiting the following data sets:

- a new digital terrain model integrating the land DTM of the University of Lecce with a Morelli bathymetry and DTM's of neighbouring regions from France, Switzerland, Germany, Austria and Slovenia;
- the Italian gravimetric file for land and the digitized gravimetric Morelli's map for the sea.

In the past years also some activities have been pursued in comparing a previously computed gravimetric geoid (Italgeo 90) with new data sets; in particular GPS leveling. Also some particular solutions have been elaborated by the University of Padua in the Venetian area for the purpose of calibrating the ERS1 altimeter.

Furthermore, within the framework of the European Union Geomed project, the marine geoid in the seas surrounding Italy have been computed together with the whole geoid in the Mediterranean. Finally an important activity for future geoid computations/ comparisons is under development by the Italian Geographic Military Institute with the new GPS national network coinciding in 500 points with the national leveling network.

International Geoid Commission

National Report for Japan

by

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Estimation of the geoid has remarkably advanced since the establishment of the satellite altimetry. Following SEASAT and GEOSAT, ERS-1 and TOPEX / Poseidon satellites have been providing more precision data. The altimeter data have been used to determine gravity and geoid around Japan, the northwest Pacific region and the East Antarctica (Fukuda, 1990; Segawa et al., 1991; Matsumoto and Kaminuma, 1993).

Since the satellite altimetric sea surface heights are contaminated with the sea surface topography caused by ocean dynamics, it is necessary to remove the component of the sea surface topography from altimetric sea surface heights in order to obtain an accurate ocean geoid. The determination of sea surface topography, therefore, is very important for obtaining a precise marine geoid. Ganeko and Fuchida (1992), Ganeko et al. (1994), Sengoku and Ganeko (1994) and Nishida et al. (1994) are the efforts to detect sea surface topography caused by various oceanographic phenomena by using altimeter data of GEOSAT, ERS- I and TOPEX / Poseidon. Short wavelength components of the ocean geoid undulations are effectively detected from repeated altimeter observations ocean geoid along satellite ground tracks (e.g. Sengoku and Ganeko, 1994).

A set of geoid map in and around Japan was published at a scale of 1:1,000,000, which is the same scale of a bathymetric chart series of the Hydrographic Department of Japan, based on the geoid data from Ocean Research Institute, University of Tokyo (Fukuda et al., 1993).

Kuroishi (1993) computed geoid undulations around Japan mainly using and marine gravity data.

The regional geoid obtained by satellite altimetry data can be used to detect the relationship between the deformation of the plate and the sub-bottom structure (Matsumoto and Kaminuma, 1993). Several GEOSAT tracks across the circum-Antarctic ridges were examined to investigate the characteristics of geoid anomaly and to detect the sub-bottom structure.

One approach to overcome the difficulty of a large set of linear equations needed to the Least Squares Collocation is to divide the matrix into small pieces by a multi-step collocation. A test computation was successfully carried out to estimate a very detailed local geoid (Fukuda, 1991).

Since the GPS survey directly determines the height of the Earth's surface from a reference ellipsoid, its combination with ordinary levelling and / or gravity measurements provides us several kinds of the gravity field quantities such as gravity anomaly, gravity disturbance and geoid height. Fukuda (1993) presented a proper formulation to use the Least Squares Collocation as a mean to deal with GPS, levelling and gravity for a local problem.

The ellipsoidal height differences obtained from simultaneous GPS observations can be used to determine geoid height differences with topographic heights by levelling observations. Yabuta (1993), Yamamoto et al. (1994), Tabei et al. (1994) and Yamamoto (1995) determined local geoid undulations in the Japanese land areas by GPS observations. The estimated geoid height differences were almost consistent with the previous works, such as the JHD geoid and the ORI-89 geoid, based on gravity anomalies and satellite altimeter data. Yabuta (1993) discussed a large-scale upheaval of the geoid in the Kii Peninsula, the southern Kinki District. He showed that the upheaval was strongly influenced by topography and that isostatic equilibrium did not exist in that region.

Shibuya et al. (1990, 1991) determined the geoid height at Breid Bay of Antarctica by the combined observation of satellite Doppler positioning, GPS measurement, and ocean tide observation. Their method is appropriate for dense installation of geoid height control stations along the circum-Antarctic coast.

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International Geoid Commission

National Report for Malaysia

by

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There are four major geoid related activities currently carried out by the Department of Survey and Mapping Malaysia (DSMM). These activities are tidal observation, precise levelling, gravity and GPS survey. Each activity was implemented at different time from 1983 to 1989.

The tidal observation project was initiated in 1981 with the primary objective of establishing a new Peninsular Malaysian Geodetic Vertical Datum (PMGVD) to replace the old Land Survey Datum (LSD) 1912 which was based on a year tidal observation at Port Swettenham (Now Pelabuhan Kelang). The PMGVD is the national reference of height system in Peninsular Malaysia and its height is defined by orthometric height referenced to the mean sea level termed geoid for a period of 10 years from 1984-1993 at Pelabuhan Kelang. Presently there are 12 tide stations through out peninsular Malaysia and the observation data recorded are used for the publication of annual tidal prediction table and the record of the tidal observation.

Now, the precise levelling network is based on the new PMGVD and it will be connected to all the 12 tide gauge stations that are available in Peninsular Malaysia. The network will be used to control the second class levelling. Currently three methods of levelling are used, these methods are motorised levelling, digital automatic and conventional method. To date, the precise levelling network is almost 60% completed mostly at the southern region of Peninsular Malaysia.

There are three orders of gravity survey available in Peninsular Malaysia. The main purpose is to determine the orthometric correction for the precise levelling network. The first order has been completed with 180 stations which are about 50 km apart, running along the precise levelling routes while the second order is to densify the existing first order gravity network with 1-5 km between stations. Third order gravity with an accuracy of 50 microGals were planned to cover the accessible areas of Peninsular Malaysia with spacing of 5 km grid and are used for the purpose of determining the geoid undulation in Peninsular Malaysia.

GPS survey was first introduced to Malaysia by SWEDSURVEY in 1989. The GPS technique has been used to establish a new geodetic Scientific Network for Peninsular Malaysia. This network will further be densified from 30 km to 10 km between stations for the purpose of geodetic, mapping, and scientific work.

DSMM is currently undertaken a cooperative project with UNSW for the investigation of Malaysia Height Datum and to produce a precise local geoid of Peninsular Malaysia. This project is directly related to all the activities mentioned above.

International Geoid Commission
National Report for the Netherlands

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Gravity surveys

In 1989 the Survey Department of Rijkswaterstaat and the Faculty of Geodetic Engineering of the Delft University of Technology decided to start a geoid project for the Netherlands. The goal of this project is to obtain the best possible geoid, aiming at cm precision for relative geoid heights. The gravity network has been set up in four stages. Four absolute stations have been measured, 50 first order points and 8000 second order points on land. Besides these land measurements, gravity measurements have been done on the Ijsselmeer and Waddenzee, which are inner waters in the Netherlands. The complete network supplies us with a gravity field description in the Dutch area with the possibility to obtain cm geoid precision.

In 1991 and 1993 absolute gravity measurements were executed on four stations in the Netherlands. All these measurements have been done by the Institut für Erdmessung of the Hannover University with their JILA-G3 instrument. In 1991 three stations have been visited, Westerbork, the satellite observatory in Kootwijk, the Faculty of Geodetic Engineering in Delft.

In 1993 measurements have been done again in Kootwijk and at the seismic station in Epen. The difference at the Kootwijk station with respect to the 1991 value was $+17 \cdot 10^{-8}\, ms^{-2}$. The station in Epen turned out to be one of the most stable ones in Europe, due to the foundation of this building on the Carboon. The results of all these absolute gravity measurements are reported in (Strang van Hees et al., 1995).

The first order gravity network consists of about 50 points. This network is densified by the second order network with a density of one gravity point for every $2 \times 2km^2$. This gives 8000 gravity points in the Netherlands which have been measured from 1990 to 1994.

Geoid computation:

For the Dutch geoid computation procedure it was decided to use numerical integration over mean blocks of about $5 \times 5km^2$ up to 5 degrees from the geoid computation points. The evaluation of numerical integrals like Stokes' can be done very efficiently by applying Fast Fourier Techniques. Originally FFT was applied in flat surface approximation which needs many approximations. Strang van Hees (1990) suggested a new approach where the integral is evaluated on the sphere, and not on a plane, with only few approximations. Later, Haagmans ct al. (1993) further developed this method such that no approximations are necessary at all, and exactly the same result is obtained as from straightforward numerical integration. This ID-FFT method is now internationally widely in use in geoid computation procedures and will also be used in the Dutch geoid computation procedure.

If the gravimetric geoid computation is performed a gravimetric geoid is obtained with a precision of about 2-3 cm over 100 km distance. Haagmans and Van Gelderen (1991) have shown that the gravimetric geoid may have errors of long wavelength due to errors in the geopotential coefficients. These errors may be corrected by using GPS. It is expected that the ellipsoidal height differences up to 200 km can be determined with a precision of 1 cm. Using 20 points covering the entire Dutch area, it is possible to correct the gravimetric geoid and obtain a GPS / gravimetric geoid with a precision of 1 cm over all distances. This geoid result can be used to determine orthometric heights by GPS measurements and for datum transformations. In 1996 a GPS network will be finished by the Rijksdriehoeksmeting. This network consists of about 500 stations with inter-station distances of 15 km. The expected precision of the height component is 1 cm for distances up to 50 km, so that a very good control of the GPS / gravimetric geoid will be possible. There are also about 35 deflections of the vertical available which will also give an independent control of the quality of the gravimetric geoid.

International Geoid Commission

National Report for New Zealand

by

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The only geoid activity for New Zealand that I am aware of is being undertaken at the University of New South Wales in Sydney, Australia.

An employee of the New Zealand Department of Survey & Land Information, Merrin Pearse, has a departmental study award for PhD study. This includes investigations into development of a geoid model for New Zealand under the supervision of Associate Professor A.H.W. Kearsley. The department has supplied GPS observations on precise level benchmarks and a digital elevation model for testing in a pilot area.

International Geoid Commission

National Report for Norway

by

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Geoid

A new and improved gravity dataset for Norway has been compiled. The land gravity dataset now includes measurements made by NGU, Norges Geologiske Undersoekelse, and data from other sources compiled by NGU. In addition we have identified and deleted several errors in our database. These errors were typically of order 15 mgal due to an erroneous "Potsdam-correction". At sea we have readjusted our old sea-gravity measurements from 1970-71. Comparisons with other sea-gravimetry and internal reports suggested that there might be a bias-error of order 5 - 10 mgal in these data. We used the line organized dataset made by the private company Amarok. This dataset was then separated into more than 80 separate subsets of connected lines. Each of these subsets were then subject to several cross-over comparisons with other sea-gravimetry and profile-interpolation (geogrid, Forsberg). Based upon these results we identified separate biases for each subset.

Terrain-corrections

New terrain-corrections have been computed based upon a 100 m x 100 m digital terrain-model for the inner zone (¡ 5 km) and a 1 km x 1 km model for the outer zone using Forsberg's tc program.

Geoid control

As a control of existing and new geoid models the nordic countries in 1992 established the Scandinavian West East Traverse, SWET, where we measured with GPS at levelling bench-marks of which 11 are in Norway.

International Geoid Commission

National Report for Poland

by

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In 1961 an astro-gravimetric determination of the geoid for the area of Poland was performed at the Institute of Geodesy and Cartography in Warsaw. The first gravimetric geoid for the territory of Poland computed by the collocation-integral method (Łyszkowicz, 1993) comprised about 6000 free-air gravity anomalies. In the second gravimetric solution (Lyszkowicz and Denker, 1994) a new gravity data (about 14000 mean anomalies) and topographic information from Poland territory were included. In 1994 a new attempt was made towards a detail geoid and quasigeoid determinations for the Poland territory. For this purpose, high resolution mean gravity data with the spacing 2 km x 2 km have been made available for the whole area of Poland. The computation was carried out using integral formulas evaluated by spherical Fast Fourier Transform (FFT). The final results; geoid and quasigeoid are presented in a form of contour line map, also in digital form for a regular grid with a mesh size 1.5 x 3.0. The comparison of the latest solution with GPS / levelling derived geoidal heights shows an agreement better than 10 cm / 100 km.

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International Geoid Commission

National Report for Portugal

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In the period 1991 - 1995 the following activities took place:

- Acquisition of new gravimetric data for the computation of the geoid model in the Iberian Peninsula, whose first results have already been published. This work is being carried out in a cooperation between the Instituto Português de Cartografia e Cadastro (IPCC) and the Instituto de Astronomia y Geodesia da Universidade Complutense de Madrid.

- A re-computation of the astro-geodetic geoid for Portugal is being performed by the IPCC. The results will be published in the revue "Cartografia e Cadastro":

- In 1993 a small observation campaign with a photo-zenital camera, in the region of Estremoz took place in order to compute a local geoid model. This work was a cooperation between IPCC and the Technical University of Zürich.

- The computation of the geoid in the Atlantic, in a zone between the Azores and Portugal mainland is being performed by the Faculdade de Ciências da Universidade de Lisboa.

International Geoid Commission
National Report for Switzerland

by

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Abstract

The aim of new geoid and quasigeoid determination in Switzerland with an accuracy of only a few centimetres is realised by a combined evaluation of all information on the gravity field (deflections of the vertical, gravity values, levelling, GPS measurements). By including detailed mass models one can also interpolate in regions where less dense gravity field information is available. Between 1990 and 1992 about 100 stations were observed with the transportable zenith camera of ETH Zürich. This yielded deflections of the vertical with an accuracy of better than 0.5" in general. The national GPS network, which is connected to the 1st order levelling lines, was completed in the same period. In 1993 and 1994 the mass model was completed and a priori calculations were carried out. The results showed that by including only astro-geodetic observations an accuracy of about 4 cm can be reached. If all available GPS/levelling stations are included an accuracy of about 2 cm can be obtained. The assumption in these calculations is that the quality of the GPS heights and the levelled heights is better than 1 cm. This is certainly too optimistic, especially for GPS heights. As a further step the influence of varying the variance-covariance functions of the collocation approach was investigated.

1. Preparation of the observations

All the astro-geodetic observations of the years between 1980 and 1993 were re-evaluated with the PPM star catalogue, which is of better quality than the original AGK3 catalogue. With the exception of some stations where the changes are in the order of about 0.5", the results showed no significant changes in the astronomical coordinates.

In general the evaluation of the national GPS network (LV95) has been completed. The accuracy of the ellipsoidal heights in rugged areas is on the order of about 5 cm. This accuracy is not adequate to contribute to a high precision geoid determination. Thus the available heights enable checking of the astro-geodetic geoid determination. Therefore it is foreseen to repeat the observation on some selected stations. Particular attention will be given to the modelling of the tropospheric corrections by making use of dedicated microwave water vapour radiometers.

2. Mass models and reduction of observations

The most important part of the density model is the 25-meter digital height model DHM25. Today 80 percent are available and the whole country should be covered by early 1996. One problem with this model is that until now only the surfaces of the lakes are digitized. Therefore, a special model for the water masses of the lakes was required. The bottoms of the lakes will be digitized in a second step after the completion of DHM25.

The software for calculating the effects of topography and local density anomalies on the gravity field has been completed.

A further important model is describing the depth of the crust-mantle boundary (Moho). The results of the project "Tectonics and Deep Structure of the Western and Southern Swiss Alps" to determine the crustal structure beneath the Alps could be used to compile an improved model.

Other models incorporated in the geoid calculations are the Ivrea body, the sediments of the Po plain and the molasse basin of the central plateau.

3. A priori calculations

An important step consisted of the a priori calculations of the accuracy of the geoid determination. So far gravity measurements have not yet been included. However results have showed that in most parts of Switzerland an accuracy of better than 4 cm can be reached by using the astro-geodetic information only. Maximal a priori errors of about 6 cm turned up only in the region of Geneva and in some valleys of the southeast where only sparse astronomical data are available.

These accuracies can be improved with GPS/levelling measurements. If all stations of the national GPS network could be included, a maximal formal error of 1.5 cm could be obtained. Other investigations with a less dense distribution show that a geoid calculation with an accuracy of about 3 cm seems to be realistic. To achieve this result, it is necessary to include about 4 GPS/levelling stations with a height accuracy of 1 to 2 cm. How much the gravity measurements can improve these results has to be investigated yet.

4. Tests of the variance-covariance functions

In collocation the chosen variance-covariance function and its parameters are decisive in the way the residuals are interpolated. Three different covariance models were tested:

a) The 2-dimensional 3rd order Markov Model as used by Gurtner during the last national geoid computation.

b) An inverse distance model, as used by Wirth in different local geoid computations. In Wirth's investigations no significant differences to model a) were found. The advantage of this model is its short calculation time.

c) A 3-dimensional version of the 3rd order Markov model. This version results in a higher correlation between stations at the same altitude. As a consequence, stations in the valleys have a higher weight for the geoid calculation than stations on the mountains.

The comparison of models a) and b) showed that the differences of the resulting geoid undulations are smaller than 5cm in most parts of Switzerland.

The comparison of models a) and c) resulted in no significant differences if only astro-geodetic observations were included. However, if the GPS/levelling measurements were also included, differences of up to 15 cm were reached. It seems that a three-dimensional approach results in an uncertain extrapolation to sea level.

Outlook

The next step will be to include the gravity measurements in the investigations as well. It should then become evident whether they help to improve the accuracy of the geoid or if they will only serve the purpose of comparison. In addition, the influence of the chose variance-covariance functions seems to be too large, and their parameters must be analysed further.

The final geoid calculation can be performed after the completion of the 25-meter digital height model and after the final evaluation of the national GPS network.

International Geoid Commission

National Report for Sweden

by

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The last squares modification of Stoke's formula have been further studied and numerically applied to compute a 3'x 5'geoid model for Sweden.

The effects of the Earth's terrain on geoid determination using Helmert's condensation and geopotential coefficient recovery from terrestrial as well as satellite data have been investigated. Also the terrain effects on the atmospheric potential has been studied.

In addition, studies are made on the relationship among the Fennoscandian gravity field, the Moho depth and land uplift.

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International Geoid Commission

National Report for the United Kingdom

by

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The Institute of Engineering Surveying and Space Geodesy of the University of Nottingham has continued work on using GPS heighting, particularly at Tide Gauge stations, to validate local (national) and regional (European) geoid models. The measurements from the UKGAUGE and EUROGAUGE GPS networks have been used to calculate datum offsets between mean sea level and the geoid models. (Dodson et al., 1994, Ashkenazi et al., 1994) Agreements, after removing a constant offset and ignoring local Sea Surface Topography (SST), have been found to be at the 5cm (national) and 15cm (European) rms level. Comparison has also been made with the OSU long wavelength SST model. Additionally, work has been carried out in assessing the use of geoid models for height aiding of GPS, for offshore positioning in the North Sea.

University College London, Department of Photogrammetry & Surveying, is involved in geoid determination for peninsular Malaysia and Zimbabwe. Both regions are characterised by a sparse and uneven distribution of terrestrial gravity data. A preliminary gravimetric geoid for three test areas in peninsular Malaysia has been estimated by the method of least squares collocation (LSC) using a tailored global model, local gravity data, and height data. The geoid height computations were also carried out using the fast Fourier transform algorithms (FFT), mainly for comparison reasons. Numerical results based on a comparison of the preliminary gravimetric geoid heights with those available control data derived by GPS and levelling have been analysed in terms of both the absolute and the relative differences. Preliminary work for Zimbabwe has, to date, focussed on an assessment of the available data and its compatibility with existing global solutions, together with an analysis of the potential for terrain correction in this region.

Work at the University of Edinburgh has included the development of computational algorithms to allow the combination of heterogeneous gravity data sets, namely satellite altimetry measurements of geoid height and surface (ship-borne and land) gravity observations. Tests with simulated data indicate 1 cm stability in the iterative interpolation algorithm, and the procedure has been used with real data to produce a 5 km gridded model of the gravity field of the North Atlantic (Kirby and Hipkin. 1994). Further investigations have considered the magnitude of error sources in computing high resolution geoid and height anomaly models for local areas. This work involved a rigorous, high precision computation for an area of central Britain and concluded that the British geoid model EDIN891 is at the sub-centimetre level of precision for wavelengths up to about 300 km (Hipkin, 1994). Gravity observations along the channel tunnel (Hipkin et al., 1994) have been used to compute normal heights from an Ordnance Survey reciprocal heighting profile.

At Oxford University a project to produce a gravimetric geoid of the British Isles with 2 km resolution and an estimated accuracy of 8 cm was completed (Featherstone and Olliver, 1993 and 1994). The method employed Stokes integral with a modified kernel over an optimised cap size, in conjunction with a geopotential model. A project to compute a gravimetric geoid for East Africa is under way.

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International Geoid Commission

National Report for the United States of America

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The past four years have again seen significant advances in geoid computations. In fact, the number of references has more than doubled over the last report. One of the most exciting new developments of this period has been the production and dissemination of digital data sets through CD-ROM media and the INTERNET network. For this reason, a section devoted to "electronic publication" of digital resources can be found at the end of this report.

National Geoid Computation

During this period, a new high-resolution geoid model, GEOID93, was released by the National Geodetic Survey (NGS) (Milbert and Schultz, 1993a). This model incorporated new terrain corrections, improved quality gravity data (courtesy of DMA), the second order term of the normal gravity gradient, and the OSU9 I A model. Also, for the first time, a 3'x 6' high-resolution geoid was computed for the state of Alaska. Two deflection of the vertical models, DEFLEC90 (Milbert 1994d), and DEFLEC93 (Milbert and Schultz, 1993b) were also computed and released by NGS in this period. These models use cubic splines of geoid profiles to develop deflections at the geoid. The deflections are then upward continued by the normal curvature of the plumbline correction. However, with the new deflection model for Alaska, the actual curvature of the plumbline is modeled by a variant of Eq (5.32) pg.195 of Heiskanen and Moritz.

A New Global Geopotential Model under Construction

R.H. Rapp and R.S. Nerem (1995) report on a joint Goddard Space Flight Center / Defense Mapping Agency (GSFC/DMA) project to compute an improved 360 degree spherical harmonic model of the Earth's geopotential. This model will incorporate the latest satellite tracking data, as well as altimeter data from TOPEX / Poseidon, ERS-1, and the Geosat Geodetic Mission. The model will also incorporate new surface and ship gravity data covering the globe, including the former Soviet Union. NGS will participate in the International Geoid Service Special Working Group on the GSFC/DMA Model Evaluation, and will use the final GSFC/DMA model as a basis for a new, high-resolution, GE01D96 geoid height model. The GSFC research team is lead by R. S. Nerem, and the project manager for DMA is Larry Kunz.

A Book devoted to the Geoid

The book, "Geoid and Its Geophysical Interpretations", edited by P. Vanicek and N.T. Christou was published in 1994. U.S. contributors were R.H. Rapp, global geoid determination; V. Zlotnicki, the geoid from satellite altimetry; R. Sailor, signal processing techniques; C. Bowin, the geoid and deep earth mass anomaly structure; B. F. Chao, the geoid and Earth rotation; and R.S. Nerem and C.J. Koblinsky, the geoid and ocean circulation. When one considers the reputations and accomplishments of these individuals and the other contributing authors, it is seen that the release of this book stands as a significant event.

Global Geopotential Models

In this period, several new geopotential models were computed, of both low and high degree. In addition, significant work was done in accuracy analysis of these models. For a perspective on the progress in this field, Vetter (1994) provides a history from the earliest geopotential models to our current status.

In the area of techniques, Lerch (1991) reports on a data weighting method, utilizing data subset adjustments, to compute geopotential models with heterogeneous, satellite-only data sets.

In the area of accuracy analysis, we can begin with an assessment of GEM-T1. Lerch, Patel, and Klosko (1991) compare the GEM-T 1 (satellite tracking data only) geopotential model with 5^o anomalies derived from satellite altimetry. Bertiger, Wu, and Wu (1992) performed a covariance analysis to predict the expected improvement to GEM-T2 from 10 days of GPS-controlled TOPEX / Poseidon (T/P) data. Wu and Yunck (1992) also used this 10 day scenario with an emphasis on T/P orbits. Wagner and Klokocnik (1994) use Geosat and ERS 1 crossovers to assess the accuracy of the GEM-T2 model. By use of latitude lumped coefficients, Klokocnik and Wagner (1994) test the GEM-T2 error estimates with Geosat ERM crossovers.

Global geopotential models, GEM-T3, and GEM-T3S, complete to n=50, were computed by Lerch, et al. (1992) using satellite tracking, altimeter, and surface gravity observations. Additional description of GEM-T3 is provided by Lerch, et al. (1994). In a later study, Nerem, et al. (1994a) analyze DORIS tracking of SPOT 2 to develop a modification to GEM-T3, and then they compare this result to other geopotential models. Rapp and Wang (1993) compare the geopotential models OSU91 A, GEM-T3, and GRIM4-C2 with Doppler and GPS derived heights on vertical benchmarks.

In support of the TOPEX / Poseidon (T/P) project, Nerem, et al. (1994c) computed the JGM-1 (prelaunch) and the JGM-2 (post-launch) models, complete to n=70. Estimates indicate T/P radial orbit error at 2 cm, and geoid commission error at 25 cm for wavelengths greater than 2500 km. While a JGM-3 model has been computed, it has not yet been officially documented.

In the area of high-degree global geopotential models, Rapp, Wang and Pavlis (1991) computed the OSU91A model, complete to n=360. It should be noted that this computation included development of a sea surface topography model.

The Marine Geoid, Satellite Altimetry and Sea Surface Topography

During this period, the launch of new satellite altimetry missions and the release of subsets of the Geosat Geodetic Mission (GM), have been instrumental in major progress on the marine geoid and the synergistic improvement of Sea Surface Topography (SST) models. Beginning first with mean sea surfaces, Marsh et al. (1992) reports on MSS-9012, a global mean sea surface obtained from GEOS-3 and Seasat altimeter data. Wang and Rapp (1992) computed a mean sea surface from a year of the Geosat ERM mission and also developed some ocean variability results. In subsequent work, Rapp, Yi, and Wang (1994) computed a sea surface from cycles 4-54 of TOPEX, solved for differences with respect to the 1992 OSU surface, and got geoid gradient agreement at O.9cm / km. Bhaskaran and Rosborough (1993) perform a simulation, and demonstrate that an improved model for altimeter orbit error covariance improves the recovered regional mean sea surface. Wang and Rapp (1991) report on the impact of cross-track geoid gradients on track-averaged altimetry.

The new satellite altimetry missions, coupled with declassification of subsets of the Geosat Geodetic Mission (GM), have also given new insights into the marine gravity field. McAdoo and Marks (1992a and 1992b) and Sandwell (1992) compute and analyze the gravity fields of the Southern ocean from declassified GM Geosat data (south of 60 S). In a later release, the GM data was declassified south of 30S. Marks, McAdoo, and Smith (1993) computed this marine gravity field and reported on the Southwest Indian Ridge. A preliminary study by McAdoo and Marks (1992c) found that ERS-1 altimetry could achieve 30 km along-track resolution, but that a 35 day repeat hampered cross-track resolution. The ERS-1 data were used by Laxon and McAdoo (1994) to compute the Arctic marine gravity field up to 82N; which was then compared with shipborne data. Basic and Rapp (1992) predict gravity anomalies at 1/8 spacing by means of collocation using GEOS-3, Seasat, and Geosat altimeter data augmented by ETOPO5U bathymetry.

Geoid models in marine areas have proven to be highly effective in the measurement of Sea Surface (dynamic) Topography (SST). For example, Nerem, et al. (1994b) computes an SST field, complete to n=15 by subtracting GEM-T3 geoid height from satellite altimetry. In this case, they were able to see the El Nino. In a different procedure, Porter, Dobson, and Glenn (1992) compute a ßynthetic geoid"by subtracting SST obtained from a fluid dynamics model, from Geosat altimetry.

In studies involving the Gulf Stream, Rapp and Wang (1994) computed a 3'x 3'geoid grid using land, ship, and bathymetrically-inferred gravity, which was then used with Geosat altimetry to estimate SST. In a follow-on, Rapp and Smith (1994) used a gravimetric geoid and TOPEX/Poseidon altimetry to compute SST. A Gulf Stream velocity model was then fit to the results and compared with NOAA AVHRR data.

Martel and Wunsch (1993) did a combined inversion of hydrography, current meter data, and altimetric elevations to compute North Atlantic circulation. In this approach, their aim was an improvement of both geoid and oceanographic features.

Theory, Techniques, and Results

Again, significant progress was seen during this period. Rapp (1992) discusses the sensitivity of global geoid models to issues such as the Earth's GM, semimajor axis (a), and local vertical datums. I find this paper particularly noteworthy, since Rapp points out that one obtains a height anomaly, not a geoid height, under the standard evaluation of geopotential coefficients. The implications are far reaching, since we must now consider the kind of gravity anomaly, and the kind of "geoid" that we want to obtain from a set of coefficients. Clearly, digital terrain and density data sets, and / or related data, such as Bouguer anomalies, will play a role here. I'm sure there will be additional research presented on this topic in the future.

Even more fundamentally, questions on the definition of the geoid have been raised by Rapp (1994c). In this paper, Rapp reviews the geodetic and the oceanographic definitions of the geoid, and discusses the difficulties of realizing a geoid under these different definitions. Also of note, Heck (1991) examines the vectorial and scalar free Boundary Value Problems (BVP) and the fixed gravimetric BVP. He finds that through explicit formulation, decimeter differences can be found.

Wang (1993) describes an FFT formulation for the minimum error combination of geopotential coefficient and terrestrial gravity data. Hwang (1993b) developed an FFT method to form normals for a spherical harmonic analysis when one is given incomplete data coverage. And, Bettadpur, Schutz, and Lundberg (1992) report on data storage and CPU execution times for spherical harmonic synthesis and least squares accumulation on vectorizing supercomputers for a simulated, one month, gradiometer mission.

By means of a Gram-Schmidt orthonormalization procedure, Hwang (1991) developed a compact representation of Sea Surface Topography (SST), and found that the formulation provided better separation of SST and geoid signals in altimetry. Using the same procedure, Hwang (1993a) reports that 99.9orthonormal model.

Jekeli (1991) examines statistical tests for a Gaussian stochastic process when given a residual gravity field in a local, planar, region. Milbert (1991 e) points out the issue of vertical datum errors when combining GPS, leveling, and geoid models, and shows an adjustment approach to accommodate these errors. Lee and Mezera (1992) study interpolation of 18 GPS benchmarks in a 25 sq. mile area with a cubic hermite polynomial. While a 2 cm result was obtained, no gravity data were used, and no analysis of GPS height error was performed. Milbert (1991a) presents a family of covariance functions based on degree variance models that are efficiently evaluated by elliptic integrals.

Geoid models in local areas also received significant attention during this period. In a computation of the local geoid on the island of Maui, Smith (1992) found significant improvements when using 3"x 3"digital terrain for terrain corrections. The application of the integrated geodesy formulation in a rugged, high-altitude setting by Milbert and Dewhurst (1992) showed a requirement to use isostatic anomalies, and a need to develop an empirical cross-covariance function between gravity anomalies and anomalous geopotential. Weigel (1993) studied geoid heights obtained from variable sized caps using Meissl's modification to Stokes' method. In this work, he identified error due to vertical datum inconsistencies. Potterfield (1994) used a least-squares procedure and a Jordan 3rd-order Markov process model to relate GPS on benchmarks to high resolution geoid grids. Boener (1994) computed a high resolution, local geoid for Monterey Bay with software obtained from the National Geodetic

Survey. He estimates the accuracy at 3.5 cm at a 5 km distance, and he compared the results with ship-borne GPS to derive sea surface topography. Geoid models in three regions, North Dakota, Nevada, and, Ecuador were computed by Balde (1995) and were then used with GPS to establish orthometric heights for gravity surveys. A report on the techniques used to compute GE0ID90 can be found in Milbert (1991 f and 1991 c). An accuracy assessment of GE0ID90 for the Commonwealth of Virginia is presented in Milbert (1991b).

During a year of study at the National Geodetic Survey, Yuki Kuroishi computed several 3'x 3' models of the geoid for the nation of Japan. The adopted JGEOID93 model was found to have 8.6 cm error in a 400x600 km area, when comparing GPS/levelling data sets. This figure is comparable to the error levels seen in the United States for the GE0ID93 model in similar sized areas. One reference to this work is Kuroishi, Milbert, and Schultz (1993).

As reported at various meetings of the American Geophysical Union, GE0ID93 geoid model comparisons with over 1400 GPS/levelling points now show 23.7 cm RMS. The error is long wavelength, with a decaying exponential-type empirical covariance function model of L=450 km. When the geoid model is augmented by a long-wavelength correction computed with collocation, the residual error is 6.2 cm RMS. This error is mostly white, with a correlated part of 2.6 cm. This shows remarkable short wavelength fidelity of national models on 3' grids.

Geodetic and Geophysical Applications

In geodetic applications, Satalich (1994) used GPS leveling in a 55 km corridor on the Santa Clara River. After a trend removal, GE0ID93 showed a 1.1 cm RMS agreement. Parks and Milbert (1994) studied the effect of additional gravity in the mountainous San Diego County region of the United States. Of particular note, they found a geoid error/gravity error ratio of 3 to 4 mm/milligal. Though a GEOID93 model for Alaska, Cohen, et al. (1995) were able to relate 1964 leveling to 1993 GPS heights to detect post-seismic uplift of the Kenai Peninsula.

Wessel (1993) analyzed both the topography / bathymetry and the geoid of the Hawaii-Emperor seamount chain. He found indications of possible reheating and hotspot penetration. King and Hager (1994) developed the geoid signature of a subducting slab with temperature dependent viscosity. Their results show a requirement for higher resolution geoid models over subduction zones. And, Mitrovica and Peltier (1993) developed a new formulation for secular variation in the gravitation of a spherically symmetric, self-gravitating, viscoelastic planet when subjected to an arbitrary surface load consistent with ocean loading.

Vertical Datums

In this period, research on the definition and relationships of vertical datums has received renewed interest, with emphasis on the geoid and long geopotential connections. Pavlis (1991) performed an error analysis involving gravity data in caps combined with satellite to satellite tracking, to compute long geodetic connections for vertical datum relationships.

After considerable study of the topic, Rapp and Balasubramania (1992) report on a conceptual formulation for a world height system. In this report, they relate vertical datums by precise space positioning, geopotential models, and surface gravity in a 2^o cap. Their work indicates that one can establish a regional datum to 3 kgal cm and can compute geopotential differences (connections) to 4 to 20 kgal cm.

Balasubramania (1994) continued this method of relating vertical datums. He used modified Stokes and least-squares collocation to combine surface gravity in a cap with OSU91A values. He then obtained local accuracy to 5 cm and connections at a 5 to 23 cm accuracy. In a simplified approach, Rapp (1995) used a variant of OSU91A (n=360), where JGM-2 coefficients were substituted for OSU91A for n=2,70, in conjunction with Doppler data to compare various national vertical datums, including NGVD29 and NAVD88. A review of the concepts and status of vertical datum relationships was presented by Rapp (1994b). An argument to use the geoid as a bathymetry reference is made by Kumar (1994). Zilkoski, Richards, and Young (1992) found an inconsistency between local mean sea level heights (1960-78) and both NAVD 88 and orthometric heights computed from VLBI and GE0ID90 (Milbert 1991 f).

Digital Resources

As discussed at the beginning of this report, this period has seen massive dissemination of digital data sets through CD-ROM media and the INTERNET network. The sheer size of these data sets, their comprehensiveness, and ease of access mandate that they be documented in some fashion. In this section I focus on those data sets most likely to be of interest to those involved in geoid research. Certainly, not all data sets are available for on-line access. But, one can often find subsets or products derived from base data sets. Due to the dynamic character of electronic publication, it is impossible to provide an exhaustive listing. For this reason, World Wide Web (WWW) "home pages" are provided. Users are strongly encouraged users to browse "down" any pertinent paths, as well as browse "along" any other links they may encounter.

Home pages

`http://www.ngs.noaa.gov`	(GEOID93 and DEFLEC93)
`http://www.grdl.noaa.gov`	
`http://www.ngdc.noaa.gov`	
`http://www.nodc.noaa.gov`	
`http://www.jpl.nasa.gov`	
`http://www.usgs.gov`	
`http://info.er.usgs.gov`	
`http://helmert.mps.ohio-state.edu`	(Department of Geodetic Science and Surveying, OSU)

Pointers to various data sets of interest

`http://sun1.cr.usgs.gov/glis/hyper/guide/1_dgr_demfig/index1m.html`	– index 3" elevations
`http://fermi.jhuapl.edu/states/states.html`	– relief maps of states
`http://www.ngdc.noaa.gov:80/seg/potfld/grav.html`	– images of gravity
`http://www.nodc.noaa.gov/NODC-cdrom.html`	– index Geosat CD
`http://podaac-www.jpl.nasa.gov/TopexPoseidon_Products.html`	– index TOPEX CD

Anonymous FTP access

`ftp.ngs.noaa.gov`
`ftp.ngdc.noaa.gov`
`edcftp.cr.usgs.gov:/pub/data/DEM/250` – 3" gridded digital terrain data
`ftp.jpl.nasa.gov:/pub/topex` – images of TOPEX/Poseidon data sets

The National Geophysical Data Center (NGDC) of NOAA distributes the following CD-ROM's that could be used in geoid computation:

Gravity (1994)	–gravity point data, networks, gravity anomaly grids, geoid, and boundary data.
TerrainBase	–improved 5-minute, global, digital terrain data
Global Relief	–topography and bathymetry, coastlines, ocean gravity anomalies.
Geophysics of North America	–magnetics, gravity, seismology, and topography compiled by the Geological Society of America.
GEODAS (and Update)	–marine geophysical trackline data including bathymetry, magnetics, gravity, and seismic.

The National Oceanographic Data Center (NODC) of NOAA distributes the following sets of CD-ROM:

Geosat Altimeter Crossover Differences from the Geodetic Mission
Geosat geophysical Data Records (GDR) from the Geodetic Mission for 30^oS to 72^oS
Geosat Altimeter Data, Improved (T2 GDR) from the Exact Repeat Mission

The Jet Propulsion Lab (JPL) distributes the following sets of CD-ROM:

Product # 28 – TOPEX/Poseidon merged geophysical data record
Product # 35 – TOPEX altimeter sensor data record
Product # 36 – TOPEX altimeter geophysical data record

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