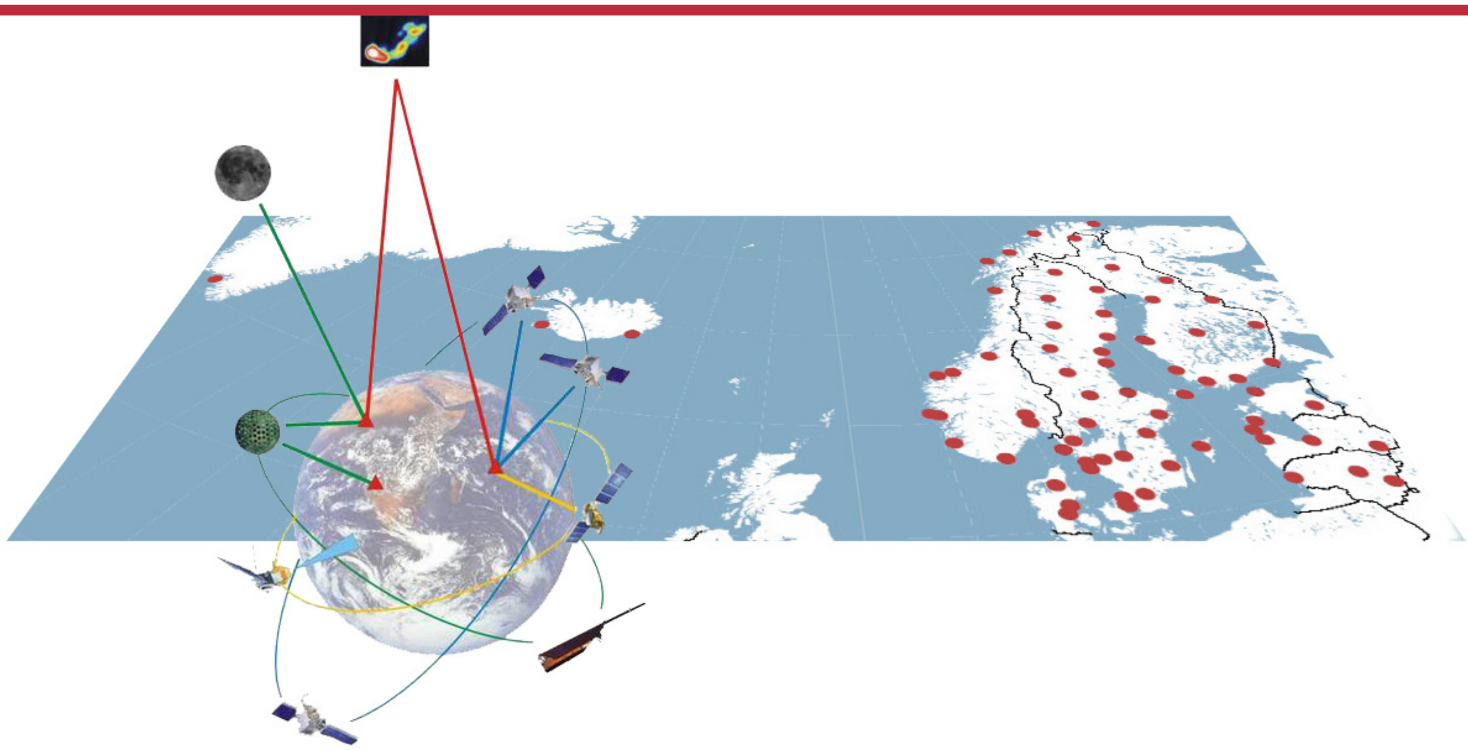
Proceedings of the 15th General Meeting of the Nordic Geodetic Commission

Copenhagen, Denmark May 29 - June 2, 2006



Edited by Per Knudsen
Technical Report No. 1, 2008

DTU Space
National Space Institute

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Nordic Geodetic Commision

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Preface

The fifteenth General Meeting of the Nordic Geodetic Commission (NKG) was held at the Royal Danish Academy of Sciences and Letters, Copenhagen, Denmark, on May 29 – June 2, 2006. There were participants from Denmark, Finland, Iceland, Norway, Sweden, Belgium, Estonia, Germany, Latvia, Poland, United Kingdom and Åland. The total number of participants was 81.

The organisers were the National Survey and Cadastre (Kort- og Matrikelstyrelsen (KMS)), and the Danish National Space Center (DNSC). The Local Organising Committee consisted of Lola Bahl (KMS - Chairman), Tycho Peter Schramm (KMS), Niels Andersen (DNSC) and Mette Weber (KMS).

The Scientific Committee consisted of Per Knudsen (DNSC - Chairman), Markku Poutanen (Finnish Geodetic Institute), Hans-Georg Scherneck (Chalmers University of Technology, Sweden), Dag Solheim (Norwegian Mapping Authority) and Mikko Takalo (Finnish Geodetic Institute). Niels-Flemming Carlsen assisted in the editing process.

During five days a total of 69 presentations were given, most of those now printed in these Proceedings. We want to express sincere thanks to all participants for their valuable contributions. There were six sessions, Positioning and Reference Frames, Gravity and Geoid, Heights and Vertical datums, Geodynamics, Earth Observation and Monitoring, and Space Missions. Moreover, there was a session discussing the future of the NKG.

The Local Organising Committee wish to thank the Royal Danish Academy of Sciences and Letters in hosting the meeting.

Copenhagen, October 23, 2008

Per Knudsen
Chairman of the Scientific Committee

NORDISKA KOMMISSIONEN FÖR GEODESI

Proceedings of the 15th General Meeting of the Nordic Geodetic Commission

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Torbjørn Nørbech, Karsten Ensager, Matti Ollikainen, Hannu Koivula, Lotti Jivall, and Martin Lidberg: Transformation from a Common Nordic Reference Frame to ETRS89 in Denmark, Finland, Norway, and Sweden

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Halfdan Pascal Kierulf and Oddgeir Kristiansen: Deformation Studies at Ny-Ålesund, Svalbard

Mette Weber: A new high-precision GPS network in Denmark

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Martin Lidberg and Jan Johansson: Management of geodetic reference frames from a Nordic perspective

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Jonas Ågren, Ramin Kiamehr and Lars E Sjöberg: Progress in the Determination of a Gravimetric Quasigeoid Model over Sweden

Jonas Ågren and Runar Svensson: On the Construction of the Swedish Height Correction Model SWEN 05 LR

Wojciech Jarmolowski: Gravimetric Quasigeoid in Southern Baltic

Harli Jürgenson, Aive Liibusk, Kristina Türk: Comparison of the Gravimetric geoid NKG04 against the geoid surface tracked by GPS on some areas of the Baltic Sea

A. Soltanpour, H. Nahavandchi: Geoid and Geoid-Type Surfaces Determination in Norway

A. Soltanpour, H. Nahavandchi: Altimetry-Derived Marine Gravity Anomaly and Its Impact to the Geoid of Norway

O.C.D. Omang: Local geoid modelling used to illustrate improved GGMs

Session 3: Heights and Vertical datums
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Tuesday, 11:20 – 11:45
Jonas Ågren and Runar Svensson: Land Uplift Model and System Definition Used for the RH 2000 Adjustment of the Baltic Levelling Ring

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Matti Ollikainen: The EUVN_DA GPS campaign in Finland in 2005

Kristian Keller, Brian Pilemann Olsen, Thomas Knudsen, Morten Nielsen, Lars Tyge Jørgensen, and Poul Frederiksen: The Accuracy of Height Models Derived by Auto-Correlation from Digital Aerial Images Obtained by a Vexcel Large Format Digital Camera

Andres Rüdja: Precise Levelling Campaign in Estonia

Mikko Takalo, Pekka Lehmuskoski, Paavo Rouhiainen and Veikko Saaranen: On digital levelling technique applied in water crossing

Mikko Takalo, Pekka Lehmuskoski, Paavo Rouhiainen and Veikko Saaranen: The Third Levelling of Finland

Karsten Engsager: UPS and DOWNS in the work by the Second Baltic Ring

Veikko Saaranen, Pekka Lehmuskoski, Paavo Rouhiainen and Mikko Takalo: The Finnish Height Reference N2000

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Michel Van Camp and Thierry Camelbeeck: Repeated absolute gravity measurements across the Roer Graben to infer tectonic deformation

Hannu Ruotsalainen: A new water level tilt meter for geodynamical research

M. Bilker-Koivula, H. Virtanen, J. Mäkinen, M. Tervo, B. Vehviläinen, M. Huttunen, R. Mäkinen: Analysis of GRACE, Superconducting Gravimeter and Water Storage Time Series

Jaakko Mäkinen, Mirjam Bilker, Fred Klopping, Reinhard Falk, Ludger Timmen, Olga Gitlein: Time series of absolute gravity in Finland

J. Mäkinen, A. Engfeldt, B.G. Harsson, H. Ruotsalainen, G. Strykowski, T. Oja, D. Wolf: The Fennoscandian Land Uplift Gravity Lines 1966–2005

Gudmundur Valsson, Thorarinn Sigurdsson, and Christof Völksen: Remeasurement of the Icelandic reference network

Jaakko Mäkinen, Hannu Koivula, Joel Ahola and Markku Poutanen: Continuous GPS observations and absolute gravity network in Dronning Maud Land, Antarctica

Martin Lidberg, Jan Johansson, Hans-Georg Scherneck, Sten Bergstrand, Glenn Milne: BIFROST: A New and Improved Velocity Field for Fennoscandia – Implications for Models of Glacial Isostatic Adjustment

Rüdiger Haas: Geodetic VLBI in Northern Europe - status and vision

M. Tervo, H. Virtanen, M. Bilker-Koivula: Environmental loading effects on GPS time series

Gabriel Strykowski et al.: Studying Fennoscandian Uplift by GRACE

Shfaqat Abbas Khan and John Wahr: Re-advance of the Qassimiut Lobe

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D. Solheim, H. Drange, J.A. Johannessen, H. Nahavandchi, O.C.D. Omang, B.R. Pettersen, H.-P Plag: Ocean Circulation and Transport between the North Atlantic and Arctic Sea -- status report 2006

Ole Andersen, Per Knudsen, Philippa Berry, Steve Kenyon, and J. Toohey: The DNSC06 high-resolution global marine gravity

Ole Andersen: Large scale hydrology and changes in gravity from GRACE

Ole Andersen, Kristine S. Madsen, and Per Knudsen: An Offshore height reference surface: Altimetric Mean Sea Surfaces (DNSC06-MSS)

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List of Participants

Van Camp	Michel	Royal Observatory of Belgium	Belgium
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Ågren	Jonas	Lantmäteriet	Sweden
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Geodetic Activities of the National Land Survey of Finland 2002 - 2005

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Introduction

During 2002 – 2005 the main geodetic activities of the National Land Survey (Maanmittauslaitos) were still concentrated on maintaining and densifying both the horizontal and the vertical control networks. Most of the densification work was done in EUREF-FIN system.

Within the NLS control surveys are done by Uusimaa and North Ostrobothnia District Survey Offices. From the beginning of 2007 control surveys will be done by Uusimaa Ditrict Survey office in whole country.

The organization of the NLS

The organisation came effective in 1999.

The NLS consists of 13 District Survey Offices, six national operational units and the central administration. The NLS has staff appr. 1800, of whom over 80% are employed in the District Survey Offices. The NLS is a governmental agency subordinate to the Ministry of Agriculture and Forestry.

District Survey Offices provide expert assistance in matters pertaining to land, real estate and maps. They carry out land surveys and help to prepare deeds of sale and provide assistance in applications for registration of title of property. They also supply cadastral information. The Offices gather and update data on the maps covering their areas for the topographic database. District Survey Offices are (see also Fig.1):

- 1. Uusimaa District Survey Office (DSO)
- 2. Varsinais-Suomi DSO
- 3. Häme DSO
- 4. Pirkanmaa-Satakunta DSO
- 5. Southeastern Finland DSO
- 6. South Savo DSO
- 7. North Savo DSO
- 8. North Karelia DSO
- 9. Central Finland DSO
- 10. Ostrobothnia DSO
- 11. North Ostrobothnia DSO
- 12. Kainuu-Koillismaa DSO
- 13. Lapland DSO

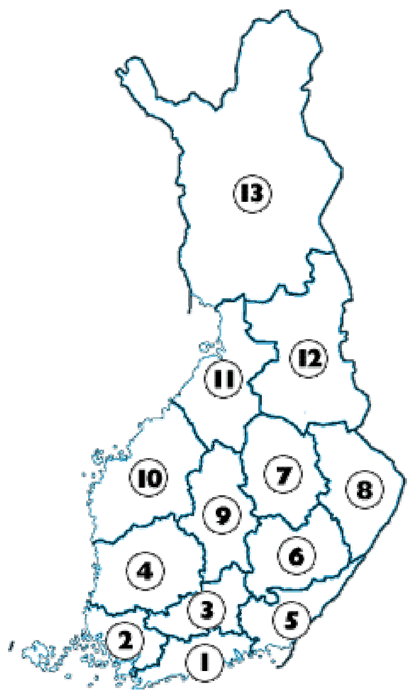

Fig. 1. *District Survey Offices and their operation areas.*

NLS's national operational units are responsible for development and research in their own areas, coordination of activities and nationwide services. Most of the units are located in Helsinki as well as the central administration. The Archive Centre is located in Jyväskylä and some parts of the Computer Centre are located in Hämeenlinna and Jyväskylä. Units are:

- The Development Centre
- The Aerial Image Centre
- The Computer Centre
- Administrative Services
- Sales and Marketing Services
- Archive Centre

Control Surveys

The NLS is responsible for Finland's lower order horizontal and vertical control networks. Within the NLS control surveys are done by the Uusimaa District Survey Office in the southern part of Finland and by the North Ostrobothnia District Survey Office in the northern part of Finland. There will become a re-organization and from January 2007 control surveys are concentrated to Uusimaa office.

The horizontal control network (and coordinate system) which is used in cadastral surveys is still based on the first order triangulation network measured by the Finnish Geodetic Institute (FGI) and partly by the NLS. The basis for the vertical control network is the precise levellings made by the FGI.

Most of the control surveys were done in order to densify the EUREF-FIN network in Finland in period 2002-2005. The aim is to densify the network measured by FGI with some 3000 points. The present status of the densification is shown in figure 2. Some work was also done in older coordinate system (kkj, kartastokoordinaattijärjestelmä).

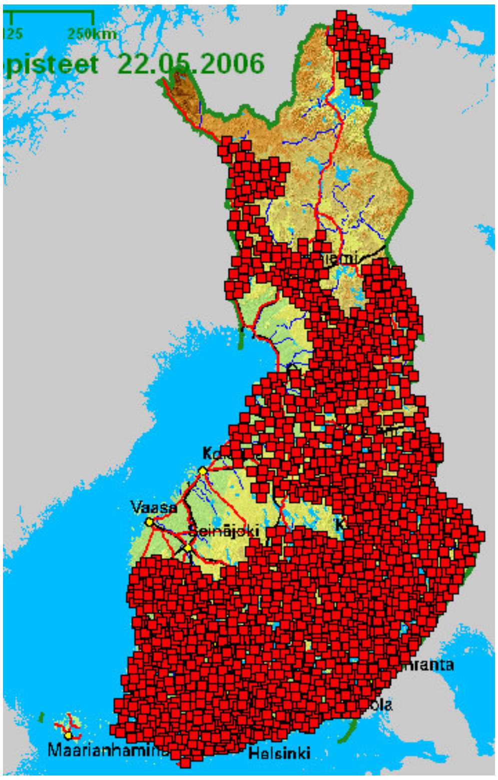

Fig. 2. *EUREF-FIN densification points*

Measurements and instruments

In the work of maintaining and densifying the horizontal control network TPS Legacy and Leica SR530 GPS receivers were used. Amounts of measured GPS stations are seen in table 1.

Year	GPS -stations	Levelled benchmarks
2002	748	622
2003	763	626
2004	807	608
2005	746	644
Total	3064	2500

Table 1. *Amounts of measured GPS stations and levelled Benchmarks by NLS during 2002 - 2005.*

In order to maintain and densify the vertical control network II and III order levellings were performed. Wild NA3000 digital levels and GPCL3 invar bar staffs were used in this work. Amounts of levelled benchmarks are seen in table 1.

Coordinates, heights and other information of the measured stations and benchmarks were stored into database and archive. A new control points register (database) was taken into use in 2004. The database consists of approximately 25 000 horizontal control points and approximately 50 000 vertical control points.

VRS – network in Finland

The NLS has taken VRS – network into use in its operations in 2003. At that time the VRS – network was covering the southern part of Finland. Since the VRS – network has been enlarged to cover the whole Finland.

The VRS- network is owned, operated and maintained by a private company Geotrim Ltd. In origin the VRS – network was established by Geotrim in co-operation with some municipalities and it was covering some areas in South Finland.

The NLS started co-operation with Geotrim in 2003, when the functionality and accuracy of VRS – concept was tested in several District Survey Offices. The benefits of VRS in fieldwork were promising and therefore a three-year contract between NLS and Geotrim was made in December 2003.

According to the contract the NLS was committed to buy services (RTK licencies) from Geotrim for three-year period. For its part Geotrim was committed to enlarge the VRS – network toward north. At start the rate of enlargement was connected to the amount of purchased RTK – licencies, but after all, the enlargement was done faster than agreed in contract.

In figure 3 the development of the VRS network is shown. The situation before the enlargement (autumn 2003) is shown with red squares. The first enlargement (situation in the summer of 2004) towards north is shown with blue colour. Before end of the year 2004 the stations with green colour were added to the network.

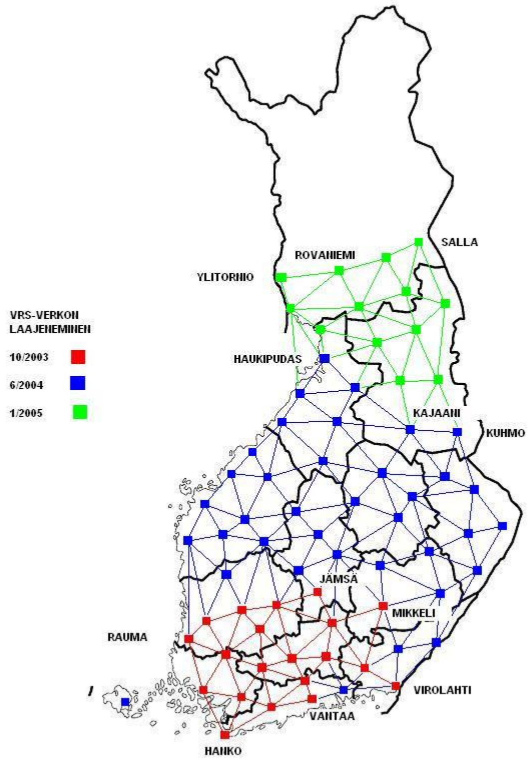

Fig. 3. The development of the *VRS-network.*

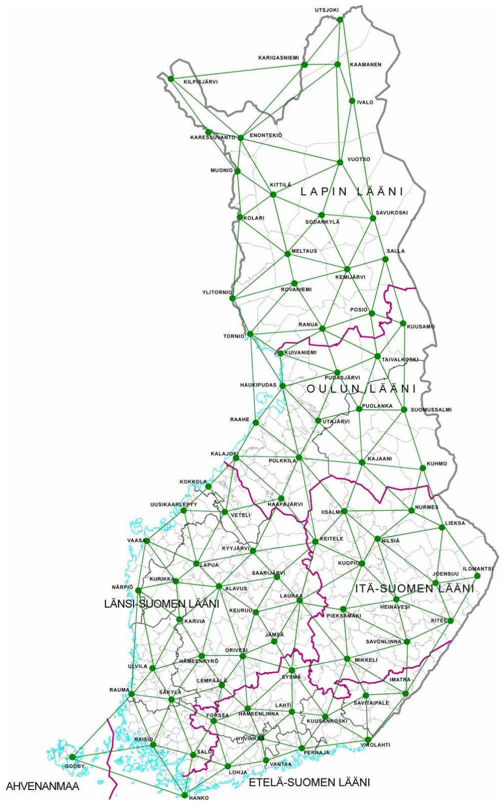

Fig. 4. The complete *VRS-network*

The enlargement was finished before the summer of 2005, when the VRS network was complete with about 85 stations. This complete network is shown in figure 4.

The VRS network is used mainly in cadastral surveys by NLS. There are approximately 200 RTK rovers using VRS corrections in NLS. Data from VRS reference stations is used also in aerial photogrammetry and in post-processing of static GPS measurements.

Other activities of NLS

Employees of the NLS took part in a working group whose topic was to prepare recommendations for public administration. The first recommendation was concerning the new Finnish national coordinate systems (EUREF-FIN) and 3-dimensional transformation between the new and old systems. In the second recommendation the map projections to be used with EUREF-FIN system were introduced. UTM-like system (ETRS-TM35FIN) was introduced for national mapping purposes (the whole Finland in one zone) and Gauss-Krüger with 1º zone width (ETRS-GKxx) was introduced for other purposes. Also the 2-dimensional transformations between the new and old systems were introduced as well as the new sheet line system for topographic maps.

There will be also a modernisation of the height system ahead. Third recommendation of the new height system is in course of preparation and it will be published in 2006.

National Report of Norway to the NKG General Assembly Meeting 2006

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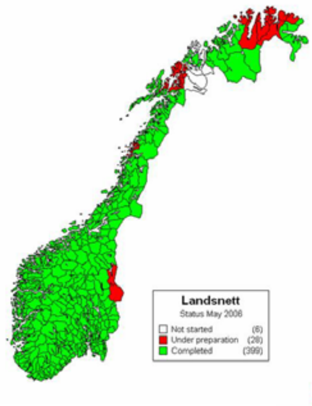
This report shows in a number of maps and photographs the status for the most important activities carried out by the Geodetic Institute at Norwegian Mapping Authority:

- Landsnett: The status of EUREF89 implementation on local level (kommuner)
- Statuskart: The status of transfer of data from local datum to EUREF89
- Height determination: Key figures for height determination in Norway
- Dekningsområde: Area coverage and permanent stations in the CPOS-service
- Planer nær framtid: Future plans for the CPOS-service
- CPOS brukergrupper: Graphical presentation of user group participation
- Permanente geodetiske stasjoner: Map showing location of permanent geodetic stations
- EGNOS-dekning: Coverage map of the EGNOS system
- Jan Mayen: Site location for a new EGNOS site at Jan Mayen
- Picture of main locations around Longyearbyen, Svalbard
- Map of main locations around Longyearbyen with location of new EGNOS site
- Picture of VLBI antenna at Ny Ålesund related to the testing of eVLBI from Ny Ålesund to Haystack
- ESEAS Network of Observing Sites – Tide gauge stations
- OCTAS/GOCINA: Map showing project areas for OCTAS (Ocean Circulation and Heat Transport between the North Atlantic and Artic Sea) and GOCINA (Geoid and Ocean Circulation in the North Atlantic)
- TOUGH - Targeting Optimal Use of GPS Humidity Measurements in Meteorology
- Subsidence Measurements of platforms in the North Sea
- Norske sjøområder: Map of location and area of Norwegian Waters
- Superledende gravimeter: Picture of the superconductivity gravimeter and its housing in Ny Ålesund. The ownership will be transferred from Japan to Norway.

The attached maps and photographs are available in Power Point from Stine Henriksen, e-mail stine.henriksen@statkart.no.

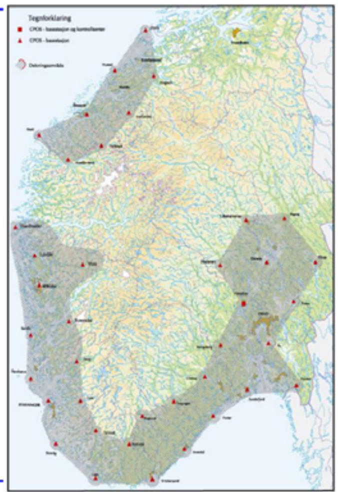
Landsnettetablering

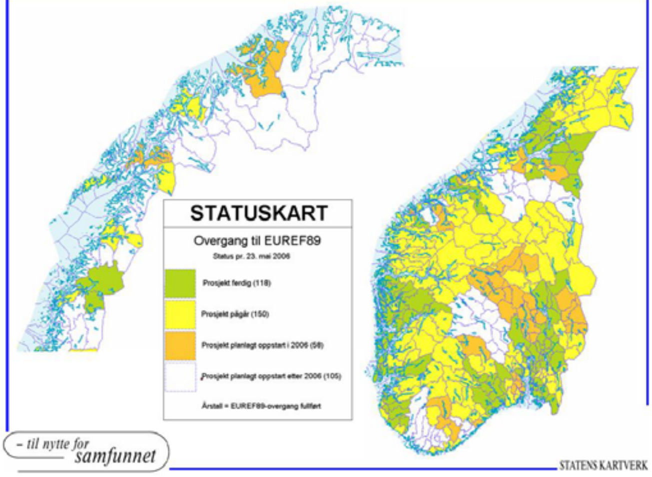


Dekningsområde

170 abonnenter pr 1. april 06

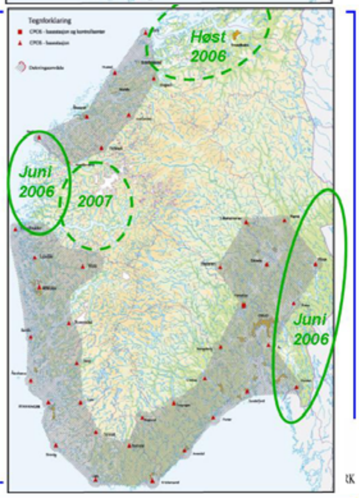
39 permanente geodetiske stasjoner inngår





Planer nær fremtid

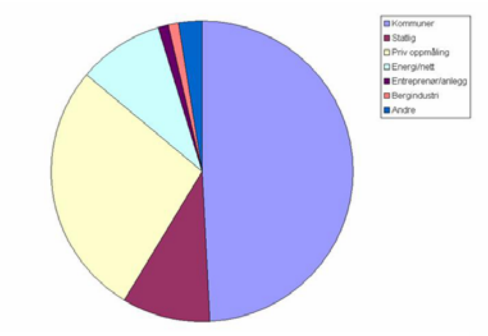
Enkeltutvidelser av eksisterende områder 2006/2007/osv
Troms vår 2007?
Finnmark 2007/2008?
Nordland 2007/2008?

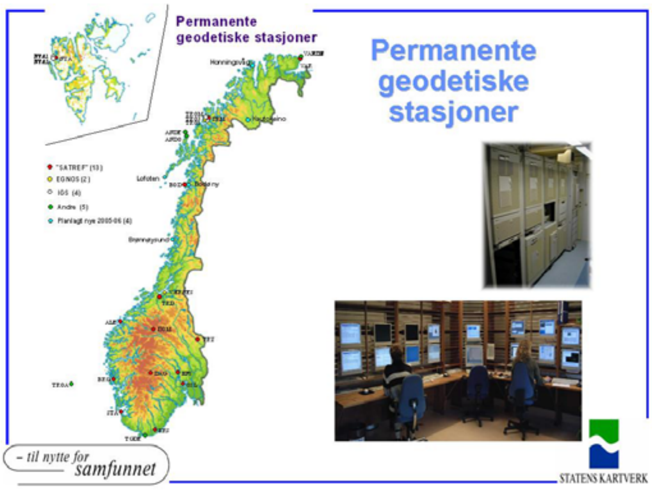


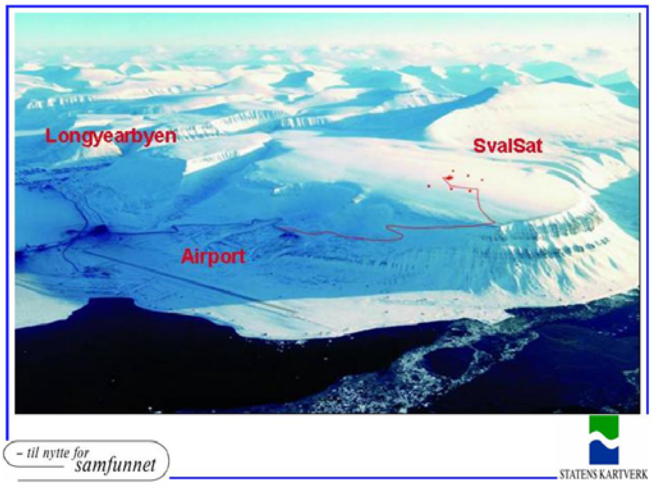
Height determination

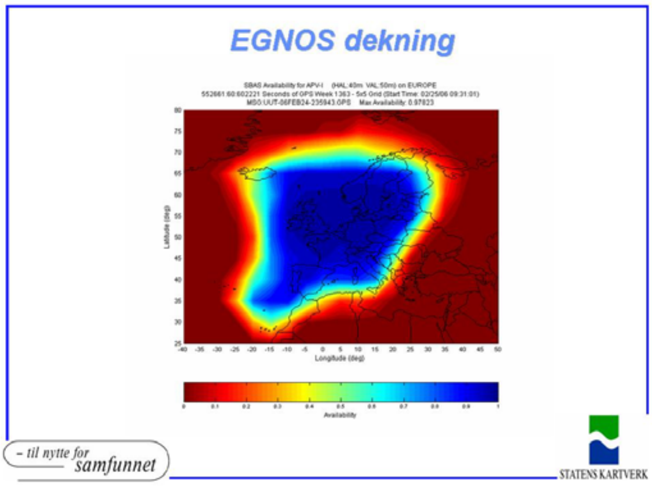
- ✓ 1840 km of double precise levelling is carried out in 2002-2005
- ✓ Final adjustment of the precise levelling network in 2006/2007
- ✓ A new vertical datum NN2000 will be introduced

CPOS brukergrupper




Permanente geodetiske stasjoner
Permanente geodetiske stasjoner
Honningsvåg
Lofoten
"SATREF" (13)
EGNOS (2)
IGS (4)
Andre (5)
Planlagt nye 2005-06 (4)
– til nytte for samfunnet
STATENS KARTVERK


Longyearbyen
SvalSat
Airport
– til nytte for samfunnet
STATENS KARTVERK


EGNOS dekning
Longitude (deg)
Latitude (deg)
Availability
– til nytte for samfunnet
STATENS KARTVERK

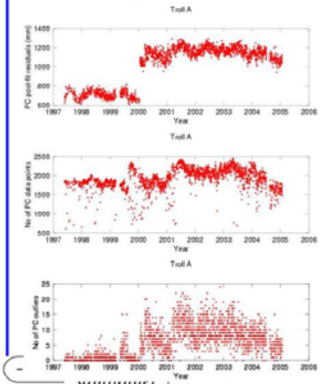

ADVENTFJORDEN
Advent City
Adventtoppen
Vestpynten
Vestpynten lykt
Hotellneset
Adventpynten lykt
Adventpynten
Svalbard lufthavn
Site Location
LONGYEARBYEN
Platå-
berget
Skjeringa
Sverdrup-hamaren
Haugen
– til nytte for samfunnet
STATENS KARTVERK

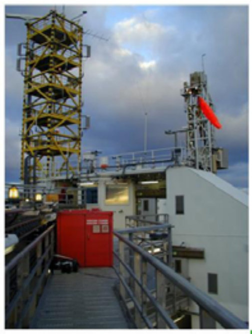

JAN MAYEN
NORD-JAN
Site Location
Airport
Ølonkinbyen
SØR-JAN
– til nytte for samfunnet
STATENS KARTVERK


Ny-Ålesund Geodetiske Observatorium
– til nytte for samfunnet
STATENS KARTVERK

ESEAS Network of Observing Sites – Tide gauge stations

Subsidence measurements of platforms in the North Sea

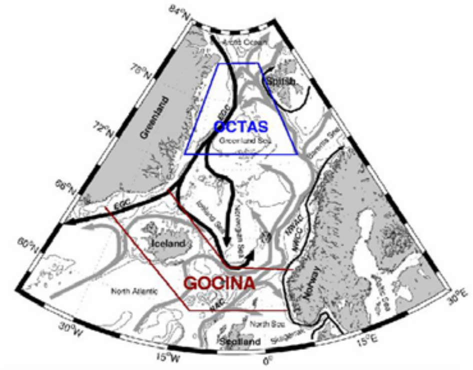




– til nytte for samfunnet

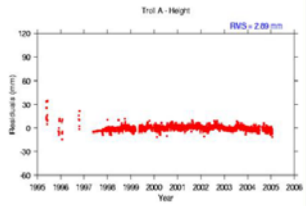
STATENS KARTVERK

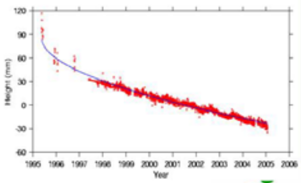
OCTAS/GOCINA



– til nytte for samfunnet

STATENS KARTVERK





STATENS KARTVERK

TOUGH
Targeting Optimal Use of GPS Humidity Measurements in Meteorology

NRT analysis at NMA

- NRT IGS orbits and EOP's
- Using hourly rinex files
  - from Norwegian permanent stations (50 sites)
  - Selected IGS sites in Europe (10 sites)
- Constrain all station co-ordinates at the current epoch
- Reference frame: ITRF2000
- 12-hour moving window
- START: 2 April 2003
- Solve for ZTD and clocks
- Timeliness:
  - Downloading of data from Norwegian stations: 2 min
  - From IGS stations: 15 min
  - GPS processing: 30 min
  - In total: 1h 45m after first measurement

– til nytte for samfunnet

STATENS KARTVERK

Norske sjøområder

– til nytte for samfunnet

STATENS KARTVERK


Superledende gravimeter Ny Ålesund
– til nytte for samfunnet
STATENS KARTVERK

National Report of Sweden to the NKG General Assembly 2006
- geodetic activities in Sweden 2002-2006

Edited by Dan Norin
Lantmäteriet
SE-801 82 Gävle, Sweden
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1. Geodetic activities at Lantmäteriet (National Land Survey of Sweden)

LANTMÄTERIET

1.1 Introduction

At Lantmäteriet (the National Land Survey of Sweden) the geodetic activities during 2002-2006 have been focused on:

- The Swedish network of permanent reference stations (SWEPOS™) including development of SWEPOS services such as a network RTK[1] service.
- The ongoing project RIX 95 with development of transformation parameters between national reference frames and local ones.
- The finalisation of the third national precise levelling and the computation of the new national height system RH 2000.
- The development of the new geoid model SWEN 05LR.
- The introduction of new reference systems such as the ETRS 89[2] realisation SWEREF 99, the new national height system RH 2000 and also of transformation strategies.
- Absolute gravity measurements on the Swedish absolute gravity sites.

Other items to mention are the Lantmäteriet web page (www.lantmateriet.se/geodesi), which has been updated with extensive geodetic information and the work that has been done to make the geodetic archive digital.

[1] RTK = Real-Time Kinematic
[2] ETRS 89 = European Terrestrial Reference System 1989

1.2 Satellite positioning (GNSS[3])

1.2.1 GPS[4] campaigns

The 2002 NKG[5] GNSMART/GPSNet Test Campaign, planned within the NKG project Nordic Positioning Service, was carried out during one month in October-November 2002 at Lantmäteriet in Gävle (Engfeldt et al, 2003). The aim was to compare two different network RTK software and the work was performed by Lantmäteriet in collaboration with KMS[6] and the Norwegian Mapping Authority.

The processing of the NKG 2003 GPS Campaign has been co-ordinated from Lantmäteriet during 2004, with a final report completed in 2005 (Jivall et al, 2005 and Jivall et al, 2006). The purposes of the campaign were to develop a unified ETRS 89 reference frame on the cm level for the Nordic area and to develop transformation strategies between ITRF[7] and the national realisations of ETRS 89. The GPS observations were carried out from September 28th to October 4th 2003 on 133 stations in the Nordic and Baltic countries.

1.2.2 NKG EPN[8] LAC[9]

Lantmäteriet operates the NKG EPN LAC in co-operation with Onsala Space Observatory at Chalmers University of Technology. Since May 2005 (GPS week 1321) the daily processing has changed from version 4.2 to version 5.0 of the Bernese software. Since the last NKG General Assembly four years ago seven stations have been added to the NKG EPN LAC sub-network, which means that totally 42 stations are processed today (figure 1.1). Lantmäteriet has also represented NKG at the fourth and

[3] GNSS = Global Navigation Satellite Systems
[4] GPS = Global Positioning System
[5] NKG = Nordiska Kommissionen för Geodesi (Nordic Geodetic Commission)
[6] KMS = Kort & Matrikelstyrelsen, Denmark
[7] ITRF =International Terrestrial Reference Frame
[8] EPN = EUREF Permanent Network
[9] LAC = Local Analysis Centre

fifth EUREF[10] LACs Workshop, which were held in 2003 and 2006.

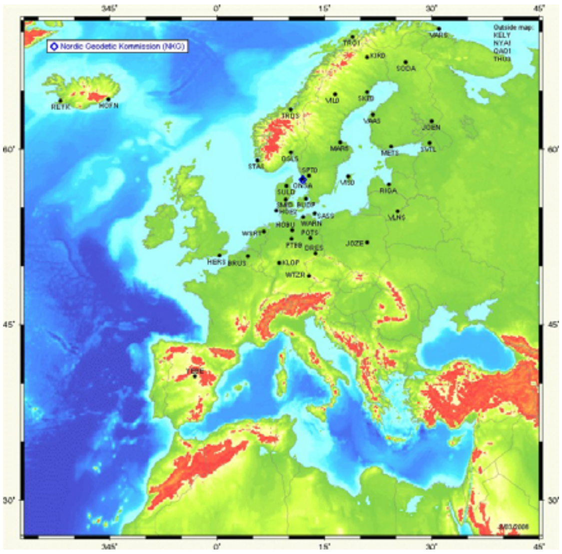

Fig. 1.1: *The NKG EPN LAC sub-network.*

1.2.3 Galileo

Staff from Lantmäteriet have participated as experts in the definition of user requirements for Galileo and in the evaluation within EU[11] of proposals in FP6[12].

1.2.4 EGNOS[13]

During 2003 an EGNOS RIMS[14] was inaugurated at Lantmäteriet in Gävle. The station has been successfully supported by Lantmäteriet since that year.

1.2.5 Nordic Positioning Service

Lantmäteriet participates in the project Nordic Positioning Service (Engfeldt et al, 2006). The major purpose of Nordic Positioning Service is both to exchange data between the networks of permanent reference stations in Denmark, Norway and Sweden and to establish common positioning services. The project also implies exchange of knowledge in the fields of operation and applications of networks of permanent reference stations.

1.2.6 Combination of GPS and inertial technique

GSE[15] was a project that in 2004-2005 demonstrated the possibility for a combination of GPS in RTK mode and inertial technique. Lantmäteriet together with the company IMEGO AB and a group of Swedish municipalities and governmental organisations were involved in the project.

[10] EUREF = the IAG Reference frame Subcommission for Europe
IAG = International Association of Geodesy
[11] EU = European Union
[12] FP6 = Sixth Framework Programme
[13] EGNOS = European Geostationary Navigation Overlay System
[14] RIMS = Ranging and Integrity Monitoring Station
[15] GSE = GPS Shadow Explorer

Fig. 1.2: *Demonstration of a combination of GPS in RTK mode and inertial technique.*

1.3 Network of permanent reference stations (SWEPOS)

Since July 1st 1998 the Swedish network of permanent reference stations (SWEPOS) is operational in IOC[16] mode, i.e. for positioning in real-time on the metre level and by post-processing on the centimetre level. Positioning in real-time on the centimetre level is today (May 2006) also possible in large parts of Sweden.

The purposes of SWEPOS are to:

- Provide single- and dual-frequency data for relative GNSS measurements.
- Provide DGPS[17] corrections and RTK data for broadcasting to real-time users.
- Act as the continuously monitored foundation of the Swedish geodetic reference frame (SWEREF 99).

[16] IOC = Initial Operational Capability
[17] DGPS = Differential GPS

- Provide data for geophysical research.
- Monitor the integrity of the GPS system.

Data from SWEPOS are also used for on-going research projects for the use of GNSS in meteorological applications.

The same 21 fundamental stations that SWEPOS consisted of when it became operational in IOC mode are still in operation. These stations are monumented on bedrock and have redundant equipment for GNSS observations, communications, power supply etc. They have also been connected by precise levelling to the national precise levelling network.

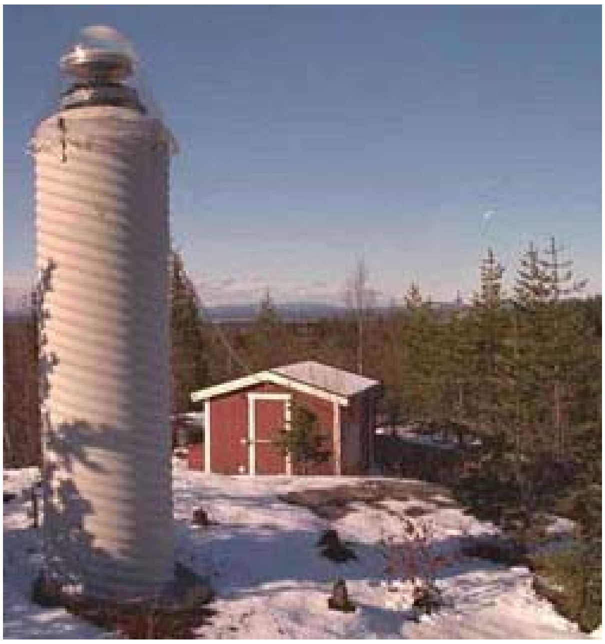

Fig. 1.3: *The fundamental SWEPOS station Vilhelmina.*

The rest of the stations that SWEPOS consists of have a variety of instrumentations and monumentations, but are mainly established on top of buildings for network RTK purposes.

Fig. 1.4: *The SWEPOS station Söderboda, monumented on top of a building.*

The total number of SWEPOS stations has since the last NKG General Assembly increased from 57 to 105 and another 16 stations will be operational during June 2006. A map with the location for all stations is shown in figure 1.6. All SWEPOS stations are equipped with dual-frequency GPS/ GLONASS[18] receivers and with antennas of Dorne Margolin type or similar.

During the four past years one more SWEPOS station (Skellefteå (SKE0)) has been included in EPN, which makes the total number of SWEPOS stations included seven (together with Onsala, Mårtsbo, Visby, Vilhelmina, Kiruna and Borås (ONSA, MAR6, VIS0, VIL0, KIR0 and SPT0)). Both daily and hourly data are delivered. Furthermore Onsala, Mårtsbo, Visby, Kiruna and Borås are included in the IGS[19] network and Skellefteå is proposed to be included.

Sweden has, according to a co-ordination done within NKG, offered all seven Swedish EPN stations except Vilhelmina for ECGN[20].

1.4 SWEPOS services

Quality checked SWEPOS data for post-processing on a WWW/FTP server in RINEX21 format has been available for a long time. So has also an automated post processing service based on the Bernese software, which is available on www.swepos.com, the SWEPOS web page. This popular service makes it possible for GPS users to automatically determine their position with centimetre accuracy using only one GPS receiver and data from the

[18] GLONASS = Globalnaya Navigatsionnaya Sputnikovaya Sistema
[19] IGS = International GNSS Service
[20] ECGN = European Combined Geodetic Network
[21] RINEX = Receiver Independent Exchange format

SWEPOS network. Some developments have been done and during 2006 it is planned that the service will change from version 4.2 to version 5.0 of the Bernese software.

The Swedish DGPS service EPOS is using correction data from SWEPOS. EPOS is using the RDS channel on the FM radio network for the distribution and is operated by Cartesia Informationsteknik AB. The wide-area differential GPS service Omnistar used correction data from SWEPOS until May 2006.

SWEPOS Network RTK service was launched on January 1st 2004. During 1999-2003, the service was preceded by both pre-study projects and projects with prototype production networks. The coverage of the service at the start is shown in figure 1.5.

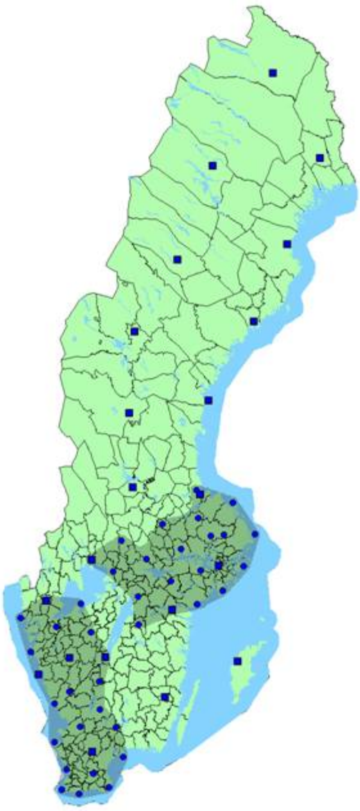

Fig. 1.5: *The coverage of SWEPOS Network RTK Service at the start in January 2004.*

The service has since 2004 been expanded by five one-year-long regional establishment projects. Two of these projects ended during 2005 (Mitt-Ost-RTK and Ost-RTK) and three are still running (Position Mitt, Gute-RTK and Nordost-RTK). The intended coverage for SWEPOS Network RTK service for 2007 is shown as the green area in figure 1.6, which includes the stations for the planned establishment project Mellan-RTK (red dots). The stations for Nordost-RTK (orange dots) will be operational during June 2006.

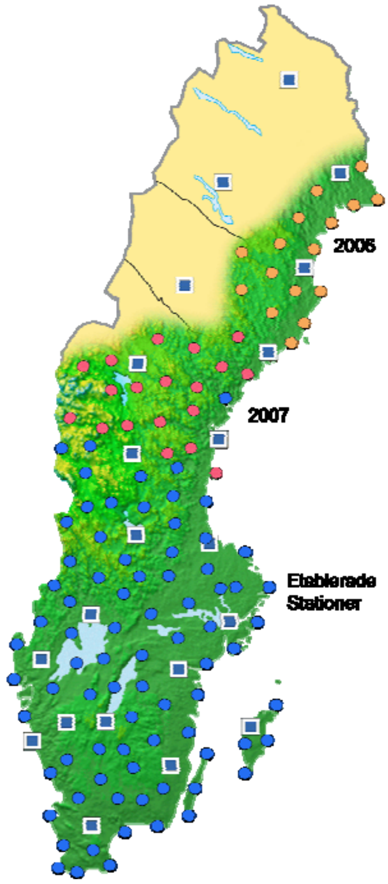

Fig. 1.6: *The SWEPOS network in May 2006. Squares are the 21 fundamental SWEPOS stations. Blue dots are the rest of the existent stations (except for a few densifications). Orange dots are stations that will become operational during June 2006 and red dots are the plan for expansion during 2007.*

The total number of subscriptions for the service has since the start in January 2004 increased from approximately 180 to approximately 450, where the users in the on-going establishment projects are not included. The service uses the network RTK software GPSNet from Trimble. GSM[22] is used as distribution channel, but since November 1st 2005, also wireless Internet (mainly GPRS[23], but also UMTS[24] or WLAN[25]) can be used. Tests have also been made to broadcast the RTK data through satellite communication and this distribution channel is also possible to use.

The network RTK service was complemented with a service that broadcasts RTK data for both GPS and GLONASS on April 1st 2006. At this date a network

[22] GSM = Global System for Mobile communication
[23] GPRS = General Packet Radio Service
[24] UMTS = Universal Mobile Telecommunications System
[25] WLAN = Wireless Local Area Network

DGPS service with nationwide coverage was also launched.

The use of SWEPOS services for construction projects has also been developed during the two past years. The SWEPOS network has been densified in two areas in the western part of Sweden for two road construction projects. Both SWEPOS Network RTK service and the post processing service have been adapted for these projects with the help of totally five new SWEPOS stations.

1.5 Development of reference systems

1.5.1 RIX 95

Since 1995, a project involving GPS measurements on triangulation stations and selected local control points called RIX 95 has been in operation. The work is financed by a group of national agencies. The principal aims are to connect local coordinate systems to the national reference frames (SWEREF 99 and RT 90) and to establish new points easily accessible for local GNSS measurements.

Concerning the connection of local coordinate systems, transformation parameters based on different transformation models are developed. The parameters are mainly based only on direct projection with Transverse Mercator, but in some cases also combined with similarity transformations in two or three dimensions. Now (June 2006) transformation parameters for 220 of the 290 Swedish municipalities are available.

The measurements in the project will be finalised in 2006. Each year about 350 triangulation stations and 500 new points (mainly existing local control points) has been measured. The present situation for the measurements is shown in figure 1.7.

To a large extent the measurements are made with standard equipment and procedures for static observations. Points with an approximate distance of 50 km are however measured in a way that very accurate coordinates in SWEREF 99 can be obtained. These points are observed for 2x24 hours with a new set up between the sessions. The observations for these points are made with Dorne Margolin T-type antennas, and the Bernese software is used for the processing.

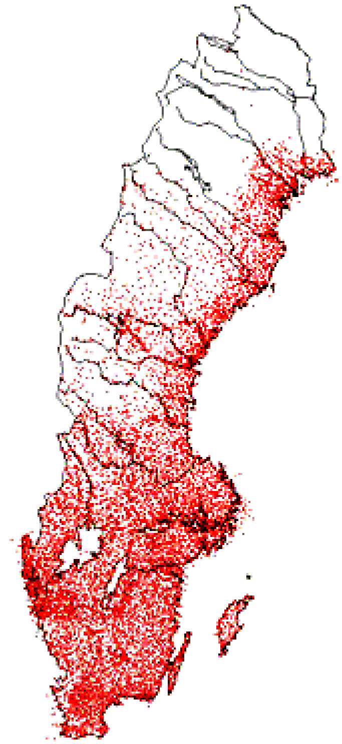

Fig. 1.7: *Completed areas in RIX 95 (May 2006).*

1.5.2 Levelling and the new national height system RH 2000

The third precise levelling of Sweden was finalised in 2003. The final adjustment for the new national height system was done in the beginning of 2005. The name of the system is RH 2000 and has 2000.0 as epoch of validity (in the perspective of the Fennoscandian glacial isostatic adjustment).

The definition of RH 2000 is done according to EVRS[26] and in co-operation with the other Nordic countries. The network consists of about 50,000 bench marks, representing roughly 50,000 km double run precise levelling measured by motorised levelling technique.

The final computation has used a land uplift model based on a combination and modification of the mathematical model of Olav Vestøl and the geophysical model of Lambeck, Smither and Ekman (Ågren & Svensson, 2006a and Ågren & Svensson, 2006b).

To get the national network connected to EVRS, the adjustment is done in a common adjustment of the nodal points in a data set called BLR[27]. The data set consists of data from mainly the Nordic countries, the Baltic states, Poland, Germany and Holland. The latter data has been provided by UELN[28]-database. The work has been done

[26] EVRS = European Vertical Reference System

[27] BLR = Baltic Levelling Ring

[28] UELN = United European Levelling Network

within NKG and will also give information about the closing error around the Baltic Sea. The Swedish network is then adjusted in a number of steps, keeping the nodal points from the BLR data set fixed.

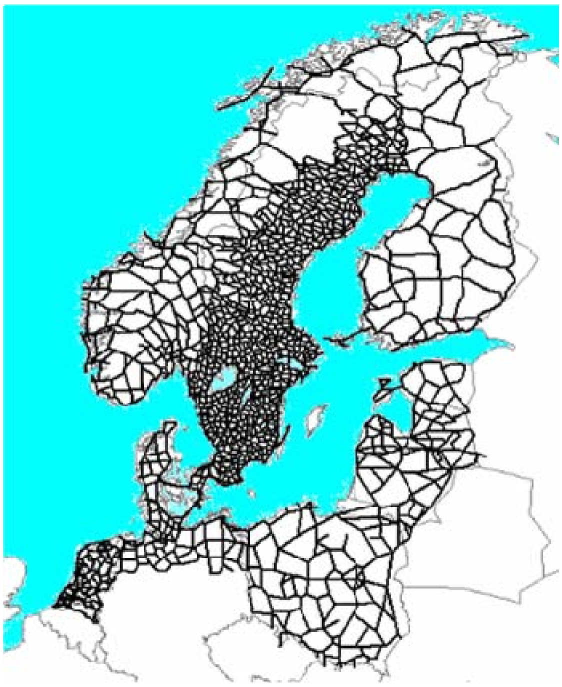

Fig. 1.8: *The BLR data set.*

1.5.3 Geoid model

A new geoid model to transform heights above ellipsoid in SWEREF 99 to heights in RH 2000 has been developed and introduced during 2005 (Ågren & Svensson, 2006c). The name of the geoid model is SWEN 05LR. The model is based on the geoid NKG 2004, calculated by the NKG working group on geoid determination. The model is then fitted on SWEREF 99 and RH 2000 using 1178 levelled points that have also been measured with GPS. Information about the residuals is also included in the model so that the users will receive heights as close as possible to RH 2000. The expected accuracy (rms) for a user is 1,5-2 cm (figure 1.9).

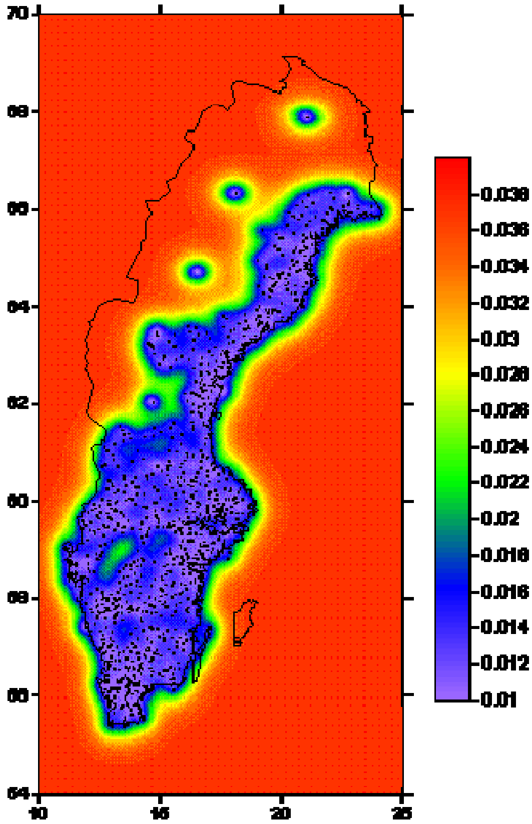

Fig. 1.9: *Expected accuracy (rms) for the geoid model SWEN 05LR (m).*

1.5.4 Gravimetric geoid determination

Lantmäteriet and KTH[29] are engaged in a joint project concerning physical geodesy and gravimetric geoid determination (see section 2.3 for further information). The main purpose of the project is to evaluate the geoid determination methods developed at KTH numerically, to compute a gravimetric quasigeoid over Sweden and to publish software for geoid determination according to the KTH methods. Some results from the project are presented as a poster at the NKG General Assembly 2006 (Ågren et al, 2006).

1.6 Introduction of new reference systems

1.6.1 Introduction of the ETRS 89 realisation SWEREF 99

Lantmäteriet has decided that SWEREF 99 shall also be the Swedish official reference frame and replace RT 90 for surveying and mapping.

A formal decision regarding map projections for national mapping purposes as well as for local surveying was taken in 2003 (Lantmäteriet 2003). All the projections are of

[29] KTH = Kungliga Tekniska Högskolan (Royal Institute of Technology), Stockholm

Transverse Mercator type and the chosen values for the defining parameters are shown in table 1.1. The introduction of SWEREF 99 in databases and in product lines at Lantmäteriet will take place in early 2007.

System	Projection parameters			
	central meridian, λ_0	scale reduction factor, k_0	false northing (m)	false easting (m)
SWEREF 99 TM	15° E	0,9996	0	500 000
SWEREF 99 12 00	12° 00' E	1	0	150 000
SWEREF 99 13 30	13° 30' E	1	0	150 000
SWEREF 99 15 00	15° 00' E	1	0	150 000
SWEREF 99 16 30	16° 30' E	1	0	150 000
SWEREF 99 18 00	18° 00' E	1	0	150 000
SWEREF 99 14 15	14° 15' E	1	0	150 000
SWEREF 99 15 45	15° 45' E	1	0	150 000
SWEREF 99 17 15	17° 15' E	1	0	150 000
SWEREF 99 18 45	18° 45' E	1	0	150 000
SWEREF 99 20 15	20° 15' E	1	0	150 000
SWEREF 99 21 45	21° 45' E	1	0	150 000
SWEREF 99 23 15	23° 15' E	1	0	150 000

Table 1.1: *Defining parameters for SWEREF 99 map projections.*

A proposal for a new map sheet division and index system has also been developed.

The work with the introduction of SWEREF 99 among other authorities in Sweden, such as local authorities, is in progress. Approximately 70 of the 290 Swedish municipalities have started the process to replace their old reference frames with SWEREF 99 and 11 have so far finalised the replacement.

To rectify distorted geometries of local reference frames, correction models can be used by the municipalities together with the transformation parameters from RIX 95. The models are based on residuals existing after transformation and the rectification is done by a so-called rubber sheeting algorithm. The result is a homogenous network in SWEREF 99 and geographical data with less deformations.

1.6.2 Introduction of the new national height system RH 2000

The work with the introduction of RH 2000 among other authorities in Sweden, such as municipalities, is in progress. Approximately 45 of the 290 Swedish municipalities have in co-operation with Lantmäteriet started the process with recalculation and analyse of their local networks, with the aim of replacing the local height systems with RH 2000. So far 4 municipalities have finalised the replacement for all activities.

1.6.3 Transformation strategies

In order to facilitate for users who still want to use local reference frames, both the transformation parameters derived from RIX 95 and the correction models mentioned in section 1.6.1 can be used. The transformation parameters are made easily accessible on the Lantmäteriet web page (www.lantmateriet.se/geodesi).

Also the geoid model SWEN 05LR used for transformation of heights above ellipsoid in SWEREF 99 to heights in RH 2000 is freely available through the Lantmäteriet web page. It is available as a grid file and also as files in both ASCII and binary formats.

1.7 Gravimetry and Geodynamics

Absolute gravity measurements in Sweden have been carried out at eleven sites (Onsala, Göteborg, Borås, Mårtsbo, Kramfors, Östersund, Arjeplog, Skellefteå (also known as Furuögrund), Kiruna (KIR0, also known as Esrange), Visby and Smögen). Totally 27 measurements on ten of the sites have been performed during the period 2002-2005 by BKG[30], IfE[31], UMB[32] and FGI[33] in co-operation with Lantmäteriet and often with field assistance from Lantmäteriet. All points are co-located with permanent reference stations for GNSS in the SWEPOS network except Göteborg. Onsala is also co-located with VLBI[34]. Smögen are co-located with a tide gauge and Visby and Skellefteå have tide gauges nearby.

[30] BKG = Bundesamt für Kartographie und Geodäsie, Germany
[31] IfE = Institut für Erdmessung, Universität Hannover, Germany
[32] UMB = Universitetet for Miljø og Biovitenskap, Norway
[33] FGI = Finnish Geodetic Institute, Finland
[34] VLBI = Very Long Baseline Interferometry

In 2006 absolute gravity measurements will be carried out on the main part of the sites by IfE and on three sites by UMB (Kiruna, Onsala and Smögen).

Fig. 1.10: *Absolute gravity sites in Sweden. The red stars (Kiruna, Arjeplog, Östersund, Mårtsbo, Skellefteå, Kramfors and Onsala) have been measured in 2003, 2004 and 2005 (Onsala twice in 2005). The purple stars (Visby and Smögen) have been measured in 2004 and 2005. The orange star (Borås) has been measured in 2003. The brown star (Göteborg) has not been measured during the period 2002-2005.*

Together with Onsala Space Observatory, a new tree dimensional velocity field for the Fennoscandian land uplift area has been computed (Lidberg 2004, Lidberg et al 2006a and Lidberg et al 2006b). It is derived from more than 3000 days of continuous observations at 53 permanent GPS stations. The results show a maximum vertical rate of 10.6 mm/yr at Umeå, which is somewhat south of current estimated location of the land uplift maximum. From internal and external accuracy assessment, the rate uncertainty for stations with the longest observation records is estimated to the 0.2 mm/yr level in horizontal components and 0.5 mm/yr for the vertical component (1σ level).

The 56° and 63° land uplift gravity lines were remeasured with relative gravimeters in a Nordic co-operation with participation from Lantmäteriet in 2003.

1.8 Further activities

1.8.1 Diploma works

During the period 2002-2006 totally 14 diploma works have been performed by students at Lantmäteriet. Ten of them have mainly been focused on GNSS and to large extend the SWEPOS services. For example have test measurements with network RTK and network DGPS been carried out to study accuracy and new distribution channels. Four of the diploma works have mainly been focused on reference systems, partly with the objective to support the introduction of new reference systems.

1.8.2 Workshops and seminars

An international workshop on network RTK was held in Gävle by Lantmäteriet in March 2004. The workshop was mainly focused on the use of the network RTK software GPSNet in different countries.

In March 2003 and 2005 seminars for Swedish GPS/GNSS users were arranged in Gävle by Lantmäteriet. The aim of these seminars was to highlight the development of GNSS techniques, applications of GNSS and experiences from the use of GNSS.

To inform and exchange knowledge between users in Sweden who are about to change to the new reference frame SWEREF 99 and the new height system RH 2000, a seminar was arranged in Gävle by Lantmäteriet in 2005.

Many locally arranged seminars have had key speakers from Lantmäteriet who informs about SWEPOS, SWEPOS services and the introduction of SWEREF 99 and RH 2000.

1.8.3 Participation in projects overseas

Lantmäteriet are through Swedesurvey involved in many projects abroad. Many projects have a geodetic part and typical components are first to update the reference frames and secondly to implement modern surveying techniques based on GNSS.

Fig. 1.11: *Amasia, one of the stations in the zero-order geodetic network of Armenia. The reference frame ARMREF 02 was ratified as a ETRS 89 realisation at the 2004 EUREF Symposium in Bratislava after presentations from personnel from Lantmäteriet.*

Countries where geodetic personnel have had assignments over the last four years are Belarus, Moldova, Georgia, Armenia, Tajikistan, Kyrgyzstan, Mongolia, Bhutan, South Africa and Namibia.

Fig. 1.12: *Personnel from Lantmäteriet introducing RTK surveying for DSLR[35] in Bhutan.*

2. Geodetic activities at the Royal Institute of Technology

The Division of Geodesy at the Royal Institute of Technology (KTH) in Stockholm offers graduate and postgraduate education as well as performs research in geodesy and surveying. Below we summarize these activities for the period 2002-2006.

2.1 Graduate programme

Geodesy courses have been taught as a part of the Geomatics Engineering specialization. The number of students attending these courses varies greatly from 5 to about 40. The following courses have been given during the period 2002-2006:

- Geodetic surveying
- Analysis of measurements (Theory of errors)
- Map projections
- Reference systems
- Satellite positioning with GPS

[35] DSLR = Department of Surveying and Land Records, Thimphu, Bhutan

- Physical geodesy
- Integrated navigation
- Engineering surveying

In the autumn of 2004, KTH started an international master programme "Geodesy and Geoinformatics". About 20 students, from Europe, Asia, Africa and Latin America, are recruited each year. From 2007, this programme will be extended to a 2-years programme in accordance with the Bologna process.

2.2 Postgraduate programme

Since 2002 two postgraduate students have completed their Ph.D.s in the field of the geoid determination (Ellmann, 2004 and Ågren, 2004). For the time being there are six active postgraduate students.

2.3 Physical geodesy and methods for geoid determination

This project is a continuation of a long-term research programme in physical geodesy at the Royal Institute of Technology (KTH) with the overall scientific objective of improving the theory and corrections needed in order to compute the geoid to 1 cm accuracy. So far most steps necessary to achieve this goal have been completed, and the developed methods seem promising. However, more tests are needed.

The main task of the current project is to carefully assess the quality of the methods. First, synthetic gravity field models were constructed and used for this purpose; they have the advantage that a true value is available. Second, a careful comparison is under way with the methods presently applied by the NKG, using both synthetic and real data. The third and fourth specific aims are to present a geoid model for Sweden, and to publish software for geoid determination according to the KTH methods. The geoid modelling runs as a joint project with Lantmäteriet. The project has a good progress both in theory and numerical view.

2.4 Technical aspects of the law of the sea

The Division of Geodesy has contributed to the work of the Advisory Board of the Law of the Sea (ABLOS; www.gmat.unsw.edu.au/ablos/), where L E Sjöberg is one of three geodesist members.

The main task has been the revision of the Technical Aspects of the Law of the Sea (TALOS), and recently the 4th edition of TALOS was published. It is freely available for downloading at (www.iho.int; publ. # S-51). A publication was also prepared in the spirit of ABLOS (Sjöberg, 2006).

2.5 Geodetic monitoring of the Vasa Ship (since 2000)

The Swedish warship Vasa was lost on her maiden voyage in 1628. For more than 330 years, she was lying 30 m below the water until 1961. Today it is standing in the Vasa Museum and has become one of the greatest attractions in Stockholm.

Great efforts have been made to preserve the Vasa ship for future generations. One of these efforts is to monitor the changes in the form of the hull and other parts of the ship. The Division of Geodesy at KTH has established a geodetic system based on total station measurement of a set of points marked by reflective tape. The measurements are related to reference network realised by corner prisms firmly mounted on the walls of the building. The measurement procedure is automated with minimum input from operator. The system is able to detect millimetre-level changes.

The project began in 2000 and since that two epochs per year have been measured. The measurements are carried out by the museum's personnel and KTH students and processed by the Division of Geodesy at KTH. The results show slow "unfolding" motion of the hull.

2.6 TNK - Inertial camera (2002 – 2004)

The project initiated by prof. K. Torlegård, funded by TFR (Swedish Technical Foundation). The goal of the project was to develop a handheld mapping system consisting of a digital camera and inertial measurement unit (IMU). Using camera observations (image coordinates from multiple images), the position of the tracked features can be computed. IMU supports the tracking algorithms and the camera observations enable the estimation of the IMU errors.

This system can be used as a surveying tool for engineering measurements, creation of maps and plans, 3D models of various objects, virtual reality models and so on. The other possible use of the system is the navigation of industrial machines, robots or navigation in the virtual reality.

The software, which was the result of this project, is being used by the company VISIMIND in the processing module of their mobile mapping system.

2.7 Monitoring of constructions and detection of motions by GPS (since 2003)

This project is funded by the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (Formas).

The goal of the project is to bring the ultimate precision of GPS into the application for monitoring measurements and for studying deformation of man-made constructions, e.g. buildings, bridges and dams and natural objects of moderate size (rock formations, slopes, atomic power plant stations and the bedrock in their surroundings). The project will focus on two components; to develop a system for monitoring and early detection of movements (section 2.7.1) and to analyse the data in various ways for an optimum detection of possible motions (section 2.7.2).

2.7.1 System development

The study will include monitoring using a single GPS receiver, a pair of receivers with one reference station and a rover and finally a rover and three reference stations. By setting up a network with one rover and three reference receivers all the above options can be studied. Controlled translations of the rover receiver will be performed by using a translation stage (device for controlled movement generation).

2.7.2 Analyses

The analyses will be both theoretical and with real data. The theoretical studies will focus on the error propagation of the measurement error into the estimated rover positioning error. In the analyses both Kalman filtering and moving averages of position will be studied. The goal is, of course, to detect a possible motion of the rover. This detection is related with the size of the motion vs. the precision of the observations as well as the time elapsed from an episodic motion, or from the time a more or less continuous motion started. If a movement larger than a certain limit is detected, the system turns on an alarm. Such system will work properly only if the limit is sufficiently large compared to precision of the monitoring sensor. Otherwise it can happen that the measurement noise can cause false alarm. How small movement can be detected depends on the precision of the measurements.

Currently, the precision (standard error) of epochwise GPS solution is about 1 cm in horizontal and 2 cm in vertical position. If there are just random errors in the GPS measurements, 64 % of errors are less than standard error. That is, 1 cm horizontal movement can be detected with GPS only with 64 % probability, 2 cm movement with 95.45 % and 4 cm with 99.99 % probability. So if we want to be 99 % sure that we do not set a false alarm, only movements larger than 4 cm can be detected. Such precision is often not sufficient. The GPS precision given above is usually stated by manufacturers and it is assumed, that one reference station is used and the roving receiver is close enough to the reference so that atmospheric (troposphere and ionosphere) and orbital errors are negligible.

2.8 Oskarshamn site investigation by GPS

During the period June 2000 to March 2004 KTH monitored crustal motions by 7, and later 11, GPS control points with baselines of 2-7 km in the vicinity of Äspö Hard Rock Laboratory near Oskarshamn in south-east Sweden.

This work, conducted on behalf of the Swedish Nuclear Fuel and Waste Management Company, was performed by repeated GPS observations 3 times per year and in total 11 campaigns. As a result of the study, 3 baselines could not be excluded from possible crustal motions of the order of 1 mm/yr, but, unfortunately, the data was collected during a period with solar maximum in 2002, and the severe ionosphere disturbances could have had some impact on the results (Sjöberg et al, 2002 and Sjöberg et al, 2004).

2.9 An un-manned GPS station at Svea, Antarctica

Since December 2004 KTH runs an automatic GPS reference station of type Trimble R7 24 channel GPS receiver (Sjöberg & Asenjo, 2006). The needed electric power of 1.8-2.3 W is generated by solar panels and a small wind generator, and the dual frequency data, recorded at a sampling rate of 15 s, is stored in a 1 GB compact flash (CF) memory. The data storage is limited by 512 (days of) observation files. The CF memory is specified to function down to – 40 degrees Celsius. So far data must be picked at Svea once per year. After the first year of monitoring at Svea, all daily data files were complete and in order. Except for being a regional reference station for all kinds of expeditions around Svea, all the GPS data recorded will contribute to the joint SCAR crustal movement GPS investigations as a link to the international reference frame ITRF.

2.10 3D laser scanning of engineering constructions and historical monuments

Terrestrial laser scanning (TLS), or 3D laser scanning, is an innovative surveying technology allowing direct and fast acquisition of high-resolution 3D images ("point clouds") of any object or environment, reflecting their existing condition.

The purpose of this project is to develop an integrated survey system consisting of a laser scanner, GPS receiver and inertial navigation system (INS), for the implementation in engineering, architectural and cultural heritage documentation projects. The work is conducted within the framework of PhD training, which is preceded by the licentiate studies. The aim of the licentiate thesis is to investigate the factors influencing TLS accuracy and develop calibration model(s) and procedures available for users.

Knowledge of the accuracy of a surveying instrument is inevitable for achieving the expected results in a project. This knowledge is obtained from calibration. Standardized calibration procedures exist for all traditional surveying instruments, and they should also be developed for terrestrial laser scanners.

During 2004-2006 we investigated three modern laser scanners – Callidus 1.1, Leica HDS 3000 and Leica HDS 2500 – at the indoor 3D calibration field established at KTH. The first two scanners have been provided by the vendors, and the scanner Leica HDS 2500 is owned by the Division of Geodesy. Based on the results of the tests, we have identified significant systematic errors in the scanners and estimated the target coordinate accuracy achieved with these instruments. We have also investigated the following issues: behavior of the range measurements over time, angular precision and accuracy and influence of the surface reflectance of different materials on the range measurements. Finally, we have proposed two simple procedures for the determination of some systematic errors in laser scanners, which might be used for in-field calibration. The results of our research are believed to improve the knowledge of the performance of laser scanners. They also create a good base for the comparison of different scanning systems and development of calibration model(s) and procedures for TLS.

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[43] SLF = Sveriges Lantmätareförening

[44] KS = Kartografiska Sällskapet (Swedish Cartographic Society)

[45] ULI = Utvecklingsrådet för Landskapsinformation

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3086 Joakim Christiansen och Magnus Tollerup. Comparisons of various methods of Trimble geodetic GPS receivers. TRITA-INFRA EX 04-016, februari 2004. (Handledare: Sjöberg)

3087 Maria Andersson. Deformationer av fasta geometrier - en metodstudie. TRITA-INFRA EX 04-012, mars 2004. (Handledare: Engberg och Fan)

3088 Johan Andersson och Daniel Renman. Studie av metod att visualisera deformationer på regalskeppet Vasa. TRITA-INFRA EX 04-066, januari 2005. (Handledare: Horemuž)

3089 Uliana Danila. Corrective surface for GPS-levelling in Moldova. TRITA-GIT EX 06-001, januari 2006. (Handledare: Sjöberg)

3090 Ingemar Lewén. Use of gyrotheodolite in underground control network. TRITA-GIT EX 06-002, januari 2006. (Handledare: Asenjo)

NKG Working Group Positioning and Reference Frames – Report 2002-2006

Per Knudsen
Danish National Space Center, Denmark

Background

The Nordic countries have implemented national realizations of ETRS89 during the 90s accommodating the needs of the NMCAs and international standards.

Presently, a Nordic Positioning Service is under development by the Nordic collaboration NKG,

Different epochs and different ITRFs for the individual national realizations caused differences up to a few cm.

Background (Resolution no. 3 - 2002)

NKG recommends for the Nordic area the development of

- a unified ETRS 89 reference frame on the cm level,
- transformations from such a reference frame to the national realizations of ETRS 89, as well as the
- transformation from ITRF to the unified ETRS 89 reference frame.

The NKG working group for Positioning and Reference frames was given the task to develop such a common Nordic reference frame and the transformation formulas.

Members:

- Finn Bo Madsen
- Karsten Engsager
- Matti Ollikainen
- Hannu Koivula
- Halfdan Pascal Kierulf
- Torbjørn Nørbech
- Runar Svensson
- Jan Johansson
- Lotti Jivall
- Per Knudsen (chairman)
- Hans-Peter Plag (NKG presidium member)
- Anna B.O. Jensen (secretary)

+ Martin Lidberg
+ Mette Weber
+ Bjørn Engen
+ Andreas Engfeldt
+ ...

Meetings:

1. Gävle (10-12 June 2003)
2. Hønefoss (30 Nov – 1 Dec 2004)
3. Copenhagen (23-24 May 2005)
4. Marsala (16-17 November 2005)
5. Onsala (29-30 March 2006)

Tasks

To establish the new common Nordic reference frame the following tasks were considered:

1. Campaign specifications, epoch, link modern geodetic monitoring stations (EPN) and original defining points
2. Data processing, more softwares, to establish the common Nordic reference frame
3. Define transformations to National ETRS89 realizations, and, furthermore, to
4. Estimate a velocity field to secure future applications, i.e. the long term stability, of the common Nordic reference frame.

Campaign specifications

133 stations (old defining bench marks and EPN stations), +Baltic +Iceland +Greenland

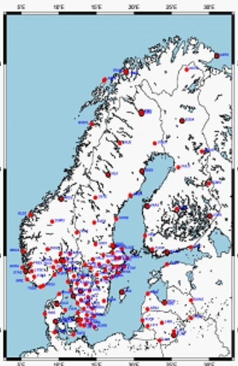
7 days,

Week 40 in 2003,

GPS week 1238,

Coordinator:

F.B. Madsen, DK/DNSC



Data processing

Softwares:

N: NMA - GIPSY

S: OSO - GAMIT/GLOBK

S: LMV - Bernese ver 5.0

DK: KMS - Bernese ver 4.2

- Use recommended settings for each programme
- ITRF 2000, epoch of the campaign (2003.75)

Coordinator:

Lotti Jivall, S/LMV

(see dedicated presentation)

The combined solution (Jivall, S/LMV)

The combined solution realize the common Nordic reference frame in ITRF2000_2003.75 fulfilling the requirements.

Estimated accuracy:

Internal: RMS of all differences (E, N, Up)

- 0.9, 1.2 and 2.5 mm after harmonization

A few large residuals after harmonization

External: Systematic, common mode errors, seasonal effects

- ~5, ~5 and ~10 mm (RMS)

Transformations

The National ETRS89 realizations have already been adopted and introduced to the users. They will not be replaced.!

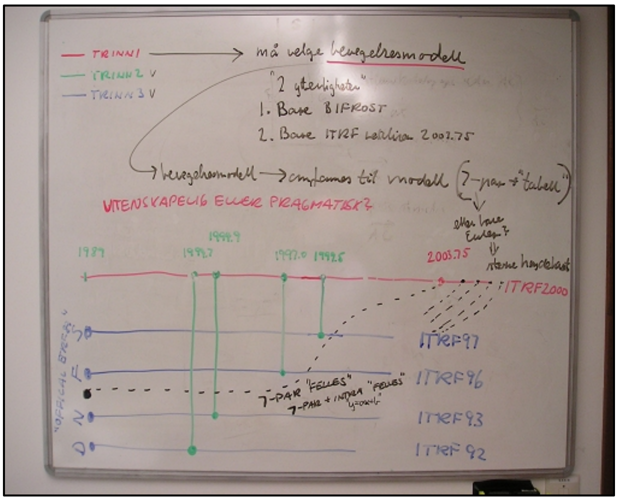
We will not promote a new ETRS89 realization, but recommend that the new Nordic frame will be in ITRF2000_2003.75.!

Define transformations directly from the ITRF200_2003.75 Nordic frame to each National ETRS89 realization.

Coordinator:

T. Nørbech, N/NMA

(see dedicated presentation)



Velocity field

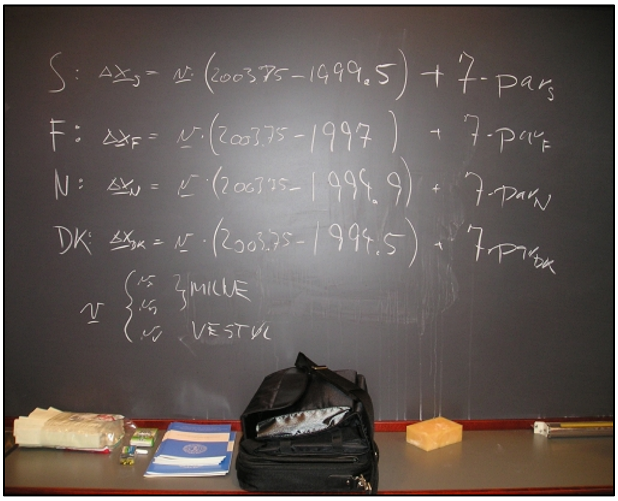
We selected:

Horizontal: Milne et al.

Vertical: Vestøl/Ågren/Svensson

Figure: Horizontal velocities from BIFROST, Milne et al, and M. Lidberg.

(See also Torbjørn)



On positioning:

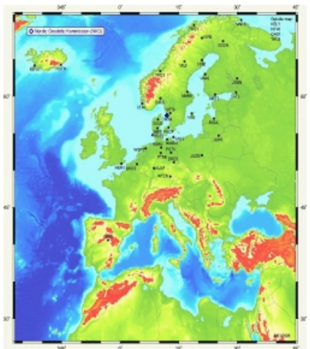
The NKG EPN Local Analysis Center
Following GALILEO developments
Feed-back to NGOS and other NKG WG activities
Feed-back to RTK project (reported by Andreas Engfeldt)
Antenna calibration...

NKG LAC sub-network (daily sol)

42 stations, mainly in northern Europe (7 added since Oct 2002)

New proposed station: SCOR (Greenland)

23 stations operated by NKG members (16 hourly data and 3 EUREF-IP)



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Bernese version 4.2 replaced with version 5.0 in May 2005

(GPS-week 1321)

Still following the processing strategy introdced by EPN GPS-week 1130

Option	Ver 4.2	Ver 5.0
Troposphere	No apriori, Dry Niell estimates	Saastamoinen aprioiri (dry Niell) Wet Niell estimates
Ionosphere	Solved for own regional model	Use global model from CODE
Ocean Tide Loading	FES95, FES99, GOT00	GOT00
Elevation cut-off	10° in all steps	3 ° in pre-proc 10 ° in final sol
Reference frame fixing	constrained	Minimum constrained

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Comparison ver 4.2 and 5.0

The result from three GPS-weeks (1318-1320) were compared between the two versions of the Bernese (ver 4.2 sol re-computed with new reference frame fixing)

Ambiguity resolution and daily repeatability slightly better in ver 5.0

Less manual interaction with ver 5.0

Differences in coordinates and troposphere parameters on a few mm

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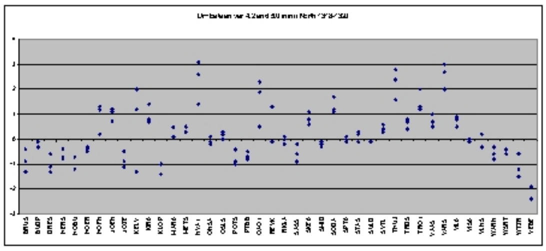
Coordinate differences North (mm)



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Coordinates - differences ver 5.0 - ver 4.2

	North (mm)	East (mm)	Up (mm)
RMS	1.0	0.6	1.9
Bias	0.2	0.6	-0.2

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Troposphere parameters – differences ver 5.0 – ver 4.2

GPS-week	Rms (mm)	Bias (mm)
1318	0.5	-2.2
1319	2.5	-1.8
1320	3.4	-2.7

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Plans

Changes in processing strategy:

Starting to use absolute antenna phase center variations (APCV)

Use gradients

FES2004 instead of GOT00 Ocean tide loading

Re-processing of the full data-set with new options

22

DANISH NATIONAL SPACE CENTER

Results

To accommodate future needs, eg a Nordic RTK service

- A common Nordic reference frame with up-dated accuracy in ITRF2000_2003.75 has been established.
- Transformations to National ETRS89 frames have been made.
- A velocity field in 3D (consistent with ITRF2000) has been selected to secure the long term stability.

Covering Greenland and Norway we have an arctic frame valuable for the IPY.

Latvia and Lithuania got new ETRS89 coordinates (to be approved by EUREF-TWG)

The NKG EPN Analysis Center

Feed-back to NGOS and other NKG activities.

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Recommendation 2006-2010:

- **We propose to continue the WG on Positioning and Reference Frames.**
- **Proposed focus for the WG in the next period:**
  - Feedback from users on the product established so far, especially from "the Nordic Positioning Service" and from other NKG WGs
  - Further development of the velocity models, including feedback to/from EUREF TWG and other NKG WGs
  - Strategy for implementation of ITRF2005
  - Possibly a new campaign including multiple techniques
  - Study and possibly further development of positioning techniques (VLBI, SLR, GNSS), including GNSS antenna calibration.
  - Give feedback to the NGOS task force.

Processing of the NKG 2003 GPS Campaign

L.Jivall (1), M.Lidberg(1,2), T.Nørbech (3), M. Weber (4)

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(2) Chalmers University of Technology, Onsala Space Observatory, Sweden, martin.lidberg@lm.se
(3) Norwegian Mapping Authority, Hønnefoss, Norway, torbjorn.norbech@statkart.no
(4) Kort og Matrikel Styrelsen, (National Survey and Cadastre), Copenhagen, Denmark, mmw@kms.dk

1. Abstract

The NKG 2003 GPS campaign was carried out from September 28th to October 4th, 2003 as a co-operation between members of NKG and the Baltic Countries. The aim of the campaign is, according to resolution No 3 of the 14th General Meeting of NKG, the development of a unified ETRS 89 reference frame on the cm level for the Nordic area and of formulas for transformation from such a reference frame to the national realizations of ETRS 89, as well as the transformation from ITRF to the unified ETRS 89 reference frame."

The campaign was processed by four analysis centres, using three different softwares:

- NMA, Torbjørn Nørbech, GIPSY/OASIS II
- OSO, Martin Lidberg, GAMIT/GLOBK
- LMV, Lotti Jivall, Bernese version 5.0
- KMS, Mette Weber /Henrik Rønnest, Bernese version 4.2

This paper presents the campaign and the processing of it. The four individual solutions and the comparison and combination of them are presented. Problems in the data analysis and differences between the solutions are discussed. The final coordinates from the campaign are in ITRF 2000 epoch 2003.75.

2. Introduction

The Nordic countries have implemented national realizations of ETRS 89. Depending on when the realizations were made and on which ITRF the realizations are based, there are differences between the realizations up to a few cm [Jivall, Lidberg 2000]. The national realizations have already been introduced to the users and will not be replaced. There are however situations were a common reference frame could be useful, e.g. for the Nordic Position Service which is under development. A common reference frame could also act as a link for transformations between the different national realizations and between the realizations and ITRF.

The full documentation of the processing part is found in [Jivall et al 2005].

3. The campaign

GPS observations for the NKG 2003 GPS campaign were carried out from September 28th to October 4th, 2003 (day 271 to 277, GPS-week 1238). The observation campaign was co-ordinated by Finn Bo Madsen at KMS, Denmark.

Stations from Denmark, Estonia, Finland, Greenland, Iceland, Latvia, Lithuania, Norway and Sweden – finally 133 stations – participated in the campaign – see figure 1 and 2.

Table 1 contains names, sorted by country, for all the observing locations. All stations are permanent except some defining ETRS 89 stations in Denmark, Latvia and Lithuania. Non-permanent stations have been written under a line.

The Lithuanian observers noticed problems with one of their stations (L311). To be sure to have this station included in the resulting coordinate set from the campaign, this station was observed for 5 extra days (292-296), ten days after the campaign together with the Lithuanian stations VLNS and KLPD.

Data were transferred to an ftp-server at KMS, Denmark, where they were checked and corrected in the preprocessing carried out by Henrik Rønnest, KMS.

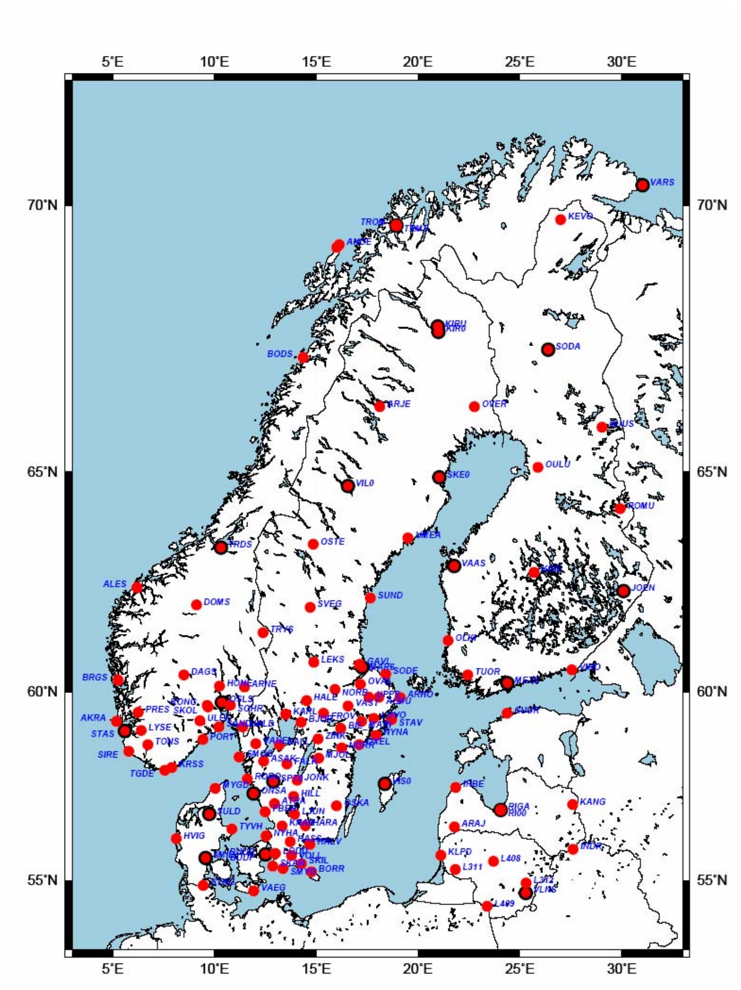


Figure 1: Stations in the Nordic-Baltic part of the NKG 2003 campaign.

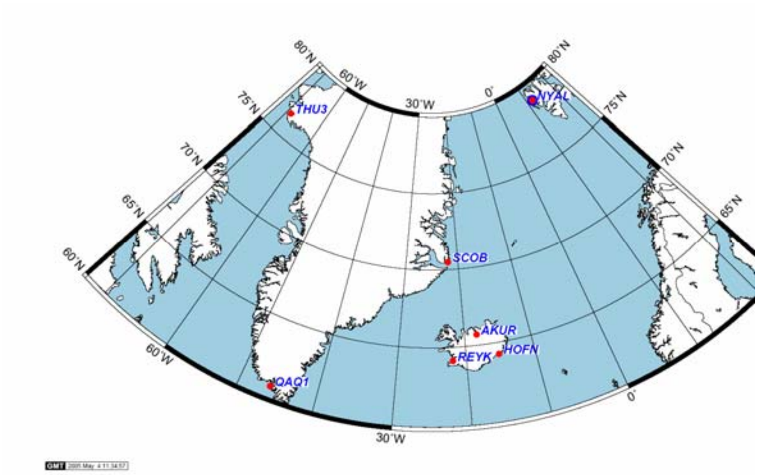


Figure 2: Stations in the Atlantic part of the NKG 2003 campaign.

Table 1: Stations included in the NKG 2003 GPS Campaign.

Denmark	TUOR	-------	PRES	FROV	OSTE
BUDP	VIRO	L311	SAND	GAVL	OVAL
SMID	VAAS	L312	SIRE	HALE	OVER
SULD		L408	SKOL	HALV	OXEL
-------	**Greenland**	L409	SOHR	HARA	RORO
BORR	QAQ1		STAS	HASS	SKAN
BUDD	SCOB	**Norway**	TGDE	HILL	SKE0
HVIG	THU3	AKRA	TONS	JONK	SKIL
MYGD		ALES	TRDS	KALL	SMOG
STAG	**Iceland**	ANDE	TRMS	KARL	SMYG
TYVH	AKUR	ANDO	TRO1	KIR0	SODE
VAEG	HOFN	ARNE	TROM	KIRU	SPT0
	REYK	BODS	TRYS	KNAR	STAV
Estonia		BRGS	ULEF	LEKS	SUND
SUUR	**Latvia**	DAGS	VARS	LJUN	SVEG
	IRBE	DOMS		LODD	UMEA
Finland	RIGA	HALD	**Sweden**	LOVO	UPPS
JOEN	--------	HONE	ALMU	MAR6	VANE
KEVO	ARAJ	KONG	ARHO	MARI	VAST
KIVE	INDR	KRSS	ARJE	MJOL	VIL0
KUUS	KANG	LYSE	ASAK	NORB	VIS0
METS	RI00	NALS	ATRA	NORR	VOLL
OLKI		NYA1	BIE_	NYHA	ZINK
OULU	**Lithuania**	NYAL	BJOR	NYNA	
ROMU	KLPD	OSLS	FALK	ONSA	
SODA	VLNS	PORT	FBER	OSKA	

4. Strategy for Processing

We decided to process the GPS campaign using the different software packages available within the group. These are:

- the Bernese GPS processing software
- GIPSY/OASIS II
- GAMIT/GLOBK

As a general philosophy for computing a GPS campaign using different software packages, we have concluded that each software package should be used together with the recommended settings for the respective software. Using this approach we will be able to check for possible differences in the result not only depending on the programs used, but also due to differences in processing strategy.

No attempt is therefore done to fully harmonise the processing strategy. We have rather tried to document how the programs are commonly used and if possible explain and compare differences.

Just for a few (but important) parameters, common recommendations were set:

- elevation cut-off = 10°

- elevation dependent weighting of the observations
- ocean tide loading corrections using the FES 99 model (values from Onsala provided for the stations in the campaign)
- no atmospheric loading correction.

The campaign was processed by four analysis centres, using three different softwares:

- NMA, Torbjørn Nørbech, GIPSY/OASIS II
- OSO, Martin Lidberg, GAMIT/GLOBK
- LMV, Lotti Jivall, Bernese version 5.0
- KMS, Mette Weber /Henrik Rønnest, Bernese version 4.2

The processing was co-ordinated by Lotti Jivall at LMV.

The four ananlysis centres processed preliminary solutions during 2004 and by the end of the year the solutions were compared and some problems were identified. Final solutions were processed in the beginning of 2005, which during the spring were combined to a final solution of the campaign.

5. NMA, GIPSY/OASIS II

Truong-An Phong processed a preliminary solution of Norway and Sweden under supervision of Torbjørn Nørbech in the beginning of 2004.

Torbjørn Nørbech carried out a new preliminary solution of all 133 stations during November 2004.

A final solution was carried out February 2005.

5.1 Characteristics of the processing

- Fiducial free Precise Point Positioning solution for all 133 stations, 5 min. epoch interval.
- JPL satellite clock corrections (yyyy-mm-dd_nf.tdp and yyyy-mm-dd_nf.tdpc), orbits (yyyy-mm-dd_nf.eci) and earth orientation parameters (yyyy-mm-ddtpeo_nf.nml).
- Local tie information is taken from RINEX file header
- Antenna type information is taken from RINEX file header
- Antenna characteristics information from the antenna file ant_info.003, including both IGS and NGS models. Mainly IGS-models but NGS-models for ASH700228D, ASH700936A_M (=B_M, D_M, E), ASH701008.01B, ASH701073.1, ASH701933B_M, ASH701945B_M (=C_M), ASH701945E_M, TRM22020.00+GP and TRM29659.00).
- Ocean loading coefficients from http://www.oso.chalmers.se/~loading/
- Float,L3 solution (no ambiguity resolution)
- 10 deg elevation cut-off
- The fiducial free solutions are then transformed with so called JPL products X-files (yymmmdd.itrf00.x) to ITRF2000. The X-files contain 7 parameters parameters for a Helmert transformation. The parameters are determined daily by JPL from a global fit on 65-70 IGS stations. So this is a global connection to ITRF2000.
- Finally the daily transformed solutions are combined to a weekly solution/solution for the campaign. This combination is performed as a least square adjustment of the daily transformed PPP solutions weighted by their corresponding co-variance information.
- The additional observations in Lithuania (L311, VLNS and KLPD, day 292-296) have also been included in the processing.

5.2 Results

The internal estimated standard deviations (from the covariance matrix of the least square adjustment) on the combined solution of seven days are:

Sx: max 1.7 mm, min 0.5 mm, average of 0.6 mm

Sy: max 1.8 mm, min 0.4 mm, average of 0.5 mm

Sz: max 2.9 mm, min 0.7 mm, average of 1.0 mm

5.3 Problems

Some modifications of the RINEX files where necessary because GIPSY is not quite RINEX compatible.

The variations of the local tie vectors at the stations L311, L312, L408,and L409 are compensated for.

The radome codes NONE, OSOD DUTD and SCIS are neglected.

Problems with processing of the Swedish stations

GAVL/273, NYHA/271, OSKA/271, OVAL/271, SKIL/271, SODE/271, UMEA/271, VAST/271, ZINK/274.

According to SWEPOS operational centre all doy 271 RINEX files have been manually edited, due to some problems. No explanation found for the stations GAVL/273 and ZINK/274 except that the ZINK/274 had ”large position change” in the s-file.

The problem was however overcome by using the program "clockprep" in the GIPSY software package to identify problems and then do manual deleting of some data. We discovered no regular pattern, but did some data deleting until GIPSY was running properly.

We have to emphasize that this manual editing is only done on one of seven days for the actual stations. The total amount of data was not dramatically reduces, except for the station ZINK/274 which was reduced by 60%.

6. OSO, GAMIT/GLOBK

Martin Lidberg processed the campaign during the summer 2004. Some antenna model errors were found, which were corrected in a new preliminary solution delivered in November 2004. The final solution was processed and delivered in February 2005, where incorrect handled horizontal GPS antenna eccentricities have been corrected.

6.1 Characteristics of the processing

- GPS observations (RINEX data) are processed using GAMIT (version 10.1) up to so called "quasi-observations" including relative station position, satellite orbits and their co-variances.
- Network solution divided into 7 sub-networks with many common stations. Additional EPN and IGS stations added to the network.
- Double differences
- Ambiguity resolution
- 10° elevation cut off
- Saastamoinen a priori troposphere model
- troposphere zenith delay parameters estimated every 2nd hour (piece-wise-linear)
- daily gradient parameters estimated
- the Niell 1996 mapping function
- a priori orbits from SOPAC
- Solving for orbit corrections
- "Quasi observations" from the 7 sub networks of the stations in the current campaign processed using GAMIT are combined with "quasi observations" of global/regional networks of IGS stations (from SCRIPPS) are combined using GLOBK.
- The connection to ITRF2000 is done in the combination (stabilization) with the global quasi observations. 39 "good" IGS stations globally distributed are constrained to IERS ITRF2000 when solving for daily Helmert parameters (3 translations, 3 rotations and a scale). This is a global connection to ITRF.
- IGS antenna models except for the antenna types ASH701008.01B, ASH701073.1, ASH701945C_M, and ASH 701945E_M, where NGS models have been used. For the site L312 the IGS antenna model ASH700228 NOTCH has been used.

6.2 Results, problems e.t.c.

Position standard errors are computed from the daily differences as $s = \sqrt{(1/n) \cdot \left\{\sum v^2 /(n-1)\right\}}$.

The standard errors are usually below 1 mm in north and east components, and below 2 mm in the vertical component. Exceptions are DOMS (e 1.5 mm), IRBE (u 4 mm), KONG (n & e 1.5 mm), L311, L312, L409 (u 4 mm) and QAQ1 (u 3mm).

The success rate of the resolved ambiguities are not presented in the result reports from GAMIT10.1, so it is not known if the fixed solutions really are fixed solutions, some baselines might be mainly (closer to) float solutions.

In the results of the GAMIT processing, the stations BRGS, HALD, KONG and SAND get phase observation residuals exceeding 10 mm which are above the usually considered acceptable level.

For the station BRGS, the daily repeatability is satisfactory in this solution. However, the east component may get bad repeatability depending on GPS processing strategy and choice of stations included in the GAMIT computation. Therefore, there are indications of possible problems in the GPS data collection at the station BRGS.

7. LMV, Bernese ver 5.0

A preliminary processing was carried out during November 2004 using version 5.0 of the Bernese Software by Lotti Jivall. Some improvements concerning exclusion of stations and replacement of the BRGS fixed solution with a float solution was carried out in February 2005.

7.1 Characteristics of the processing

- Final solution just containing GPS week 1238 (day 271-277).
- Network solution, full network 133 stations
- Double differences, baselines formed with OBSMAX strategy (maximizing the number of observations)
- ambiguity fixing (QIF)
- Orbits, EOPs and Satellite clocks from IGS
- P1-P2 and P1-C1 code biases from CODE
- Global ionosphere model from CODE

- Ocean tide loading FES 99 from Onsala
- Relative antenna models from IGS + NGS model for antenna ASH701008.01B.
- Saastamoinen apriori troposphere model (hydrostatic part) with dry Niell 1996 mapping function
- Estimating ZTD using wet Niell 1996 mapping function (2 h interval)
- Horizontal gradient parameters: tilting (24 h interval)
- 10 deg cut off , elevation dependent weighting
- Data files shorter than 12 hours were rejected
- ITRF coordinates from IGS cumulative solution (up to week 1294) used for connection to ITRF, which was done through minimum constrained adjustment with no translation condition. This is a regional constraint to ITRF.
- (Alternative connection to the EPN based ITRF was also performed)

7.2 Results, problems e.t.c.

7.2.1 Quality of daily solutions

The daily solutions of the full network were of good quality, rms = 1-1.1 mm, average rate of resolved ambiguities per day vary between 86% and 89%. The worst individual ambiguity resolution was the baseline HOFN-SCOB with 65% resolved ambiguities day 277.

The following observations were rejected because of less than 12 hours with good observations per day: MYGD day 271, IRBE, SKOL and VLNS day 272 and finally SKOL day 273. UMEA had problems with the single point positioning (determination of receiver clock correction) day 271 and was also rejected. (The same problem as was found with GIPSY/OASIS II. It should be noted that UMEA did not show any problems that day in the ordinary SWEPOS processing, which is performed with the Bernese version 4.2.)

The daily repeatability expressed in rms values are up to 2-3 mm for the north component, up to 1 mm for the east component (except for station BRGS which had an rms of 3 mm) and up to 6 mm for the up component (except for L311, L312, L409 and QAQ1 which had rms of 11-13 mm in the up-component. L311 and L409 were excluded day 273 and QAQ1 day 271 reducing the rms values to 5-7 mm for these stations.

7.2.2 Comparison between fixed and float solution

The combined float and fixed solutions were compared to each other to see if there were any possible erroneous fixed solutions. The differences are normally below 5 mm in the horizontal components, but BRGS is an outlier with 23 mm difference in the east component. The float solution of BRGS has a better agreement with the GIPSY and GAMIT solutions as well as with the long time series (5 years) of GAMIT solutions processed by Martin Lidberg. The float solution for BRGS was considered to be more reliable. Float solutions are in general noisier than fixed solutions. For this network the average rms values of the 7 days were 1, 1, 3 mm (north, east and up) for the fixed solution and 2, 3, 12 mm for the float solution. This means that just use the combined float solution (for all stations) because of the problems with BRGS is not a very good idea. We decided just to replace the fixed solution of BRGS by the float solution at this station after a Helmert fit to the 5 closest stations (ALES, DOMS, DAGS, PRES and AKRA).

7.2.3 Elevation cut-off test

An elevation cut-off test was performed by comparing the final 10°-solution with a 25°-test solution. This test indicates that the station ANDO is less accurate in height, which might be caused by the used antenna model (AOAD/M_T) not perfectly modelling the antenna and its environment at this station. Also the stations ARNE, SPT0, ARAJ, KONG, DOMS, NYA1, KUUS and L312 and have somewhat larger differences between the two solutions than normal.

7.3 Connection to ITRF2000

The connection of the final solution of LMV was made using the IGS cumulative solution. The cumulative solution up to GPS week 1294 was used, i.e. the latest solution available when the processing was carried out. This was chosen to get the best velocities for the calculation of the coordinates at epoch of the campaign.

Eleven stations from the campaign are included in the cumulative IGS solution of week 1294. Two of them are twin stations, TROM/TRO1 and NYAL/NYA1 so just one for each site was chosen for the constraint (TROM and NYAL). REYK and QAQ1 were also excluded from the constraint as they did not fit so well.

The final LMV solution is a combined minimum constraint solution of the seven days with no translation condition to the seven remaining IGS stations (METS ONSA KIRU TROM THU3 NYAL HOFN).

The rms in the Helmert fittings were 3.1 and 1.5 mm for the 3-parameter fit and the 6-parameterfit respectively on the seven IGS-stations. The improvement with 6 parameters show that there are some tilt in the GPS-solution which probably depends on systematic effects in un-modelled errors.

As a test the GPS solution was also fitted an EPN based ITRF for the Nordic-Baltic part. This coordinate set was achieved by using five weekly EPN-solution centred on GPS-week 1238 (GPS-week 1236-1240) and constraining 9 IGS stations to their IERS ITRF2000 epoch 2003.75 coordinates. (Similar approach used for the Swedish ETRS 89 realization.) This fit resulted in an rms of 1.8 mm and 1.5 mm for the 3-parameter and 6-parameter fit respectively.

The two different ITRF connections (IGS cumulative solution and the “EPN based” ITRF, respectively) have a systematic difference of 0, 1 and 5 mm for the north, east and up-component respectively.

7.4 Additional Lithuanian data

As mentioned in section 3, extra measurements were performed at the Lithuanian station L311.

First, it could be noted that when processing the original campaign, the station L311 turned out to be of the same quality as the other Lithuanian stations (though some data were missing for the first days).

To further check the station L311, the extra observations were processed and compared to the campaign solution. In this processing the EPN stations RIGA and VIS0 were added. The differences to the combined solution of the campaign (the LMV solution) are found in table 2. Both a direct comparison between the additional data and the LMV solution and a comparison of the LMV solution with and without the additional data (i.e. the corrections to the LMV solution if the additional data were added to the solution) are presented.

The differences between the campaign solution and the combined solution of the campaign and extra data were below 1 mm in the horizontal and 2 mm in the vertical component at the station L311. This comparison shows that we could be confident with the coordinates for L311 of the original campaign.

Table 2: Differences at L311. The left column contains the differences between the additional data and the LMV solution. The right column contains the differences between the LMV solution with and without the additional data

	extra-gw1238	gw1238+extra-gw1238
N (mm)	0.6	0.3
E (mm)	0.7	0.4
U (mm)	5.9	1.5

8. KMS, Bernese ver 4.2

8.1 Preliminary processing and re-processing

A first preliminary processing was carried out by Henrik Rønnest during the spring 2004 using the Bernese version 4.2. The network was processed in two parts, one Nordic-Baltic part and one Atlantic part (Greenland, Iceland and Svalbard).

Henrik’s solution for the Nordic-Baltic part was delivered in summer 2004. Lotti Jivall noticed problems with some antenna models and the coordinates used for the constraint. This was further investigated by Mette Weber. Seven antenna models were wrong affecting 33 stations and 47 baselines in the Nordic-Baltic part. Mette did a re-processing of the Nordic-Baltic part. As the time was short, the re-processing was just carried out for the affected baselines and just from the ambiguity resolution step.

In the Atlantic part of the network there were no problems with the antenna models and the solution estimated by Henrik during spring 2004 was combined with the re-processed solution for the Nordic-Baltic part forming a solution for the whole network. This solution was determined in January 2005.

8.2 Characteristics of the processing

- Network solution in six clusters; four clusters in the Nordic-Baltic part and two clusters in the Atlantic part (clusters connected with one baseline)
- Double differences, baselines formed to get the shortest distances. The same baseline definition for all days.
- Ambiguity fixing (QIF)
- Orbits, EOP’s and Satellite clocks from IGS
- Calculated own regional ionosphere model (used for ambiguity resolution)
- Ocean tide loading FES 99 from Onsala
- Relative antenna models from IGS + NGS model antennas not present in the IGS-file.
- No a priori troposphere model
- Estimating ZTD using dry Niell 1996 mapping function
- 10 deg cut off, elevation dependent weighting
- ITRF coordinates from IGS cumulative solution (up to week 1294) used for connection to ITRF

8.3 Network solution in clusters

The network was divided into six clusters A to F due to the capacity of the machine. The Nordic-Baltic part consists of cluster A to D, and the Atlantic part consists of cluster E and F. In principle the entire network was formed in a first step and afterwards divided into clusters. Therefore there will only be one baseline connecting the clusters. The network configuration is the same for each day.

During the processing one station in each cluster was constrained: BUDP (A), OSLS (B), SKE0 (C), METS (D), HOFN (E) and NYAL (F). The normal equations for each day were formed by combining the normal equations from all clusters as shown in figure 3.

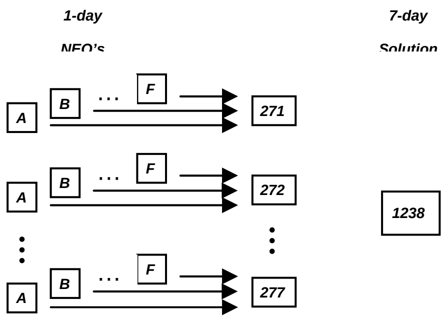


Figure 3: Combination of normal equations from each cluster, KMS solution.

In each 1-day NEQ these 6 stations were constrained. In the last step when forming the 7-day solution for the entire network selected IGS stations were constrained. This last step was not performed by KMS as explained in the next section.

8.4 Processing problems

Some stations had to be rejected for some sessions due to bad data quality or missing data. The following stations and sessions were rejected during the preliminary processing:

- RINEX-files from directory “ready” at the KMS ftp, INDR day 274 and 276 (Lotti had the same problem first but solved it by deleting a wrong “extra site info” and the observations before that)
- L312, L408, L409 day 273, missing observations
- GAVl day 276, problems with the triple difference solution
- SODE day 274, problems with the triple difference solution
- VLNS day 273, connecting baseline missing
- SKIL day 271, problems with the triple difference solution
- L311 day 271, missing observations
- QAQ1 day 271, excluded from 1-day NEQ due to high repeatability

During the re-processing the wrong antenna models were corrected. The corrections were in the order of 1-2 cm for the antenna phase centre offsets for L1 and L2. These corrections resulted in a change in the coordinates of 2-4 cm in X and Y and 8 cm in Z for the affected stations. Therefore the a priori coordinates were updated for these stations before the re-processing from the ambiguity resolution step.

The constrained coordinates in the preliminary solution were wrong. During re-processing the correct coordinates were introduced in the final step with ADDNEQ as fixed coordinates. In Bernese version 4.2 it is not possible to produce a constrained solution at a new set of coordinates with ADDNEQ. The correct coordinates have to be introduced at the beginning of the processing, which was not possible because the re-processing was only performed from the ambiguity resolution step and only for some baselines. In Bernese version 5.0 it is possible to introduce new constrained coordinates in the final step with ADDNEQ and therefore KMS provided Lotti with the 1-day NEQ-files from the KMS solution and she performed the last step of the KMS solution.

8.5 Connection to ITRF2000

The connection to ITRF2000 was done as a minimum constrained solution of the KMS NEQ-files in the same way as for the LMV solution, using Bernese version 5.0.

8.6 Results

The results were evaluated in terms of the ambiguity resolution and the rms of repeatability. The average ambiguity resolution for all baselines and all days is 66%.

The ambiguity resolution for most of the baselines is rather low; 31 baselines (i.e. 23%) have a resolution less than 60% and only 12 baselines (i.e. 9%) have a resolution of 80% or more. Generally the long baselines in the Atlantic part have the lowest ambiguity resolution of less than 50%.

Compared to the Bernese ver. 5.0 solution from LMV, KMS has a lower ambiguity resolution. Lotti and Mette made a few comparisons of some parameter settings in MAUPRP and the differences in these settings can maybe explain some of the differences in ambiguity resolution (generally more ambiguities are set up in the KMS solution, but more ambiguities are not resolved). Nevertheless, the LMV and the KMS solution seem to agree well.

The daily repeatability expressed in rms values are up to 2-3 mm for both the north and east components and up to 9 mm for the up component.

9. Comparison of the solutions from the four different analysis centres

9.1 Direct comparison of the solutions

The ITRF2000 coordinates from the different analysis centres were compared to each other. As mentioned before we have problems (related to ambiguity fixing) with the east component of the station BRGS. In the LMV solution BRGS was replaced by a float solution, since the difference between fixed and float solution was too big (23 mm in the east component) and the float solution was considered to be more reliable. In the comparison of fixed and float solutions in the KMS solution, the problems with BRGS were not so clear so the station was kept in a first comparison. It turned out that the KMS solution of BRGS differed c:a 20 mm in the east component, so BRGS was excluded from the KMS solution in the further comparisons and combinations.

The solutions agree for most stations within ±3 mm in the horizontal components and within ±10 mm for the vertical. RMS values computed on all the differences in north, east and up are 1.4, 1.5 and 4.7 mm respectively. There are however shifts between the solutions, e.g. OSO is c:a 2-3 mm south-east of the other solutions and LMV and KMS are c:a 5-10 mm below OSO and NMA. The reason for the shifts is that the connection to ITRF has been done in different ways. The OSO and NMA solutions are both global connections to ITRF while the LMV and KMS solutions are regional. Another difference is that the OSO and NMA solutions are aligned to ITRF2000 by solving for 7 parameters and the LMV and KMS solutions are aligned just with a translation.

9.2 Harmonizing the solutions

In order to better detect outliers and get an impression of the internal consistency between the solutions, we decided to harmonize/align the solutions to each other or a common coordinate set.

First all four solutions where fitted to two IGS realizations of ITRF 2000 with different number of parameters. The IGS-realizations of ITRF2000 where the weekly IGS-solution (GPS-week 1238) and the cumulative IGS-solution containing solutions up to GPS-week 1294. (Both solutions are connected to IERS ITRF2000 and not IGS 2000.)

It could be noted that the RMS for the fits with 7 parameters are on the same level for all four solutions (sigma 1.5 – 2.8 mm). The fits of the KMS and LMV solutions are improved quite a lot when a scale and rotations are solved for. The KMS and LMV scales are c:a 2 ppb. The improvement is not so large for the NMA and OSO solutions, since they already estimated these parameters, though on a daily basis.

The four solutions of the Nordic campaign were also fitted to each other with 7-parameter transformations. The two Bernese solutions (KMS and LMV) do of course agree best with each other (sigma 1.8 mm), but the agreement between KMS/LMV and OSO is not much worse (sigma 2.1 mm). The RMS for the fits between KMS/LMV and NMA is a little bit higher (sigma 3.5-3.7 mm, but still nothing to worry about). NMA has its best agreement with OSO (sigma 2.6 mm).

Regarding the translations between the solutions, LMV and NMA differ c:a 1 cm in height . KMS and OSO are in the middle. The OSO solution differs c:a 2 mm in the north component and a little bit less for the east component in comparison to the other solutions.

We decided to let the two global solutions (OSO and NMA) decide the connection to ITRF2000, as there are so many open questions concerning the regional connection of the two Bernese solutions (LMV and KMS).

An average of the OSO and NMA coordinates was calculated for each station (and component). All four solutions were then transformed to this averaged coordinate set with a 7-parameter transformation see figure 4.

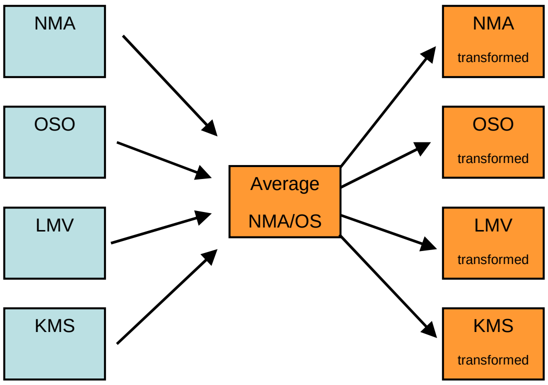


Figure 4: Harmonization of the solutions.

9.3 Comparison after harmonization

The four solutions transformed to the averaged NMA/OSO solution were compared to each other. Residuals from mean are presented in appendix A.

The differences are after this harmonization generally very small and the systematic effects seen before have (almost) disappeared. (Some small systematic effects in height are left.) The RMS values of all differences in each component are 0.9, 1.2 and 2.5 mm (north, east and up), which should be compared to the corresponding values before harmonization (1.4, 1.5 and 4.7 mm). Especially in height there is a large improvement. Just 7%, 17% and 11 % of the stations have residuals larger than 2 mm in the north , 2 mm in east and 5 mm in up, respectively.

In table 3 residuals larger than 3 mm in north and east and 6 mm in up are presented. The limits are just chosen to get a reasonable number of residuals to present. Even the largest residuals are not really much to bother about. We think that we have been able to correct/handle the real outliers, which were found when the preliminary solutions from November 2004 were compared.

The NMA solution has the largest noise and thus most of the “large” residuals. The Lithuanian stations L311 and L312 have the largest residuals in height. These stations have a quite bad repeatability in the individual solutions and e.g. in the Bernese solutions one day was excluded for L311, which might explain why we get discrepancies between the different solutions. Other differences are that different antenna models have been used for the ASH700228D antenna at L312 and that the NMA solution contains also the additional data for L311 (but according to section 7.4 the impact of these extra data is negligible).

Table 3: The largest residuals between the harmonized solutions.

Sol/comp	Station	Residual (mm)
NMA-N	L312	5,3
NMA-N	AKUR	-3,7
NMA-E	DOMS	5,2
LMV-E	KONG	4
KMS-E	KONG	3,9
NMA-E	SUUR	3,2
NMA-E	OVER	3,1
OSO-E	KRSS	-3,1
NMA-U	L312	-15,5
LMV-U	L312	11,4
NMA-U	L311	-10,1
NMA-U	ARAJ	-9,4
NMA-U	VIRO	9,3
NMA-U	QAQ1	9,1
NMA-U	RI00	-8,7
KMS-U	NALS	8,4
NMA-U	JOEN	8,1
KMS-U	KONG	-8
KMS-U	NYAL	7,9
NMA-U	KUUS	7,6
KMS-U	L312	7,5
NMA-U	KONG	6,9
NMA-U	ROMU	6,7
LMV-U	VIRO	-6,4
KMS-U	ARAJ	6,4
LMV-U	KUUS	-6,1
KMS-U	NYA1	6,1

10. Combined solution

The final combined solution of the NKG 2003 campaign is the average of the four harmonized solutions.

Using the harmonized solutions, instead of the original solutions, for an average is motivated by the fact that the agreement between the solutions is improved after harmonization. The Hemert-fits do also show that there are significant scales and rotations between the different solutions.

The choice of letting the NMA and OSO solutions define the connection to ITRF means further that we have a pure global connection to ITRF. If we should have used the Bernese solutions with regional connections as well, we would have got a mixture of global and a regional connection.

Final combined coordinates in ITRF2000 epoch 2003.75 are given both expressed as geocentric Cartesian coordinates and geodetic coordinates in appendix B.

The accuracy depends on the following components:

- Accuracy of the ITRF connection
- Systematic effects depending on un-modelled errors or wrong models
- Random errors, noise in the solutions

The accuracy of the ITRF connection could be estimated to a few mm in the horizontal components and 1 cm in height based on the direct comparison between the different solutions.

Neglected systematic effects, e.g. air pressure, might contribute to the relative uncertainty of maybe a few mm in the horizontal and half to one cm in the height component (left after the ITRF connection). Shortcomings in the used antenna models could add errors of up to a few cm. This type of error could mainly be expected for non choke ring antennas. In the performed elevation cut-off tests a few stations with possible antenna model problems were identified – see section 7.2.

The random errors in the solutions are reflected in the estimated standard errors/rms from repeatability of the four individual solutions see section 5-8 and in the comparison of the four harmonized solutions (see appendix A).

Considering the estimations in the error components above, an estimation of the real accuracy would be 0.5-1 cm in the horizontal components and 1-2 cm in the vertical on 95% level for the main part of the stations. ANDO, L311 and L312 might be less accurate in height.

11. Conclusion

Three completely different processing strategies and connections to ITRF were performed:

- Precise Point Positioning with JPL-products using GIPSY/OASISII
- Network solution with GAMIT combined with SCRIPPS global IGS-solutions for a global ITRF connection
- Network solution with the Bernese GPS software regionally connected to IGS cumulative solution (two solutions).

The resulting coordinates of the different strategies agree for most stations within a few mm horizontally and 1 cm vertically.

The internal differences are even smaller. After harmonization (transformation to the average of the GIPSY and GAMIT solution) rms of the differences are 0.9, 1.2 and 2.5 mm for north, east and up.

Also the two Bernese solutions differs in version of the program and strategy for e.g. baseline definitions and sub-division of the network, but the coordinates agree very well.

The processing in different softwares and at different analysis centres have given the final solution extra strength. Some errors were found in the comparison between the solutions and might not have been discovered if just one software at one centre had been used, e.g. bug affecting the computation of horizontal offsets, wrong antenna models and the problems with the fixed solution of the station BRGS. Comparison between fixed and float-solutions and elevation cut-off tests are useful to check the individual solutions.

The processing has indicated problems on some permanent stations, e.g. BRGS and ANDO, which need to be further investigated.

The result from the NKG 2003 campaign will be used in the development of transformations between the national realizations and to ITRF and in combination with the Nordic height solution for check of gravimetric geoids.

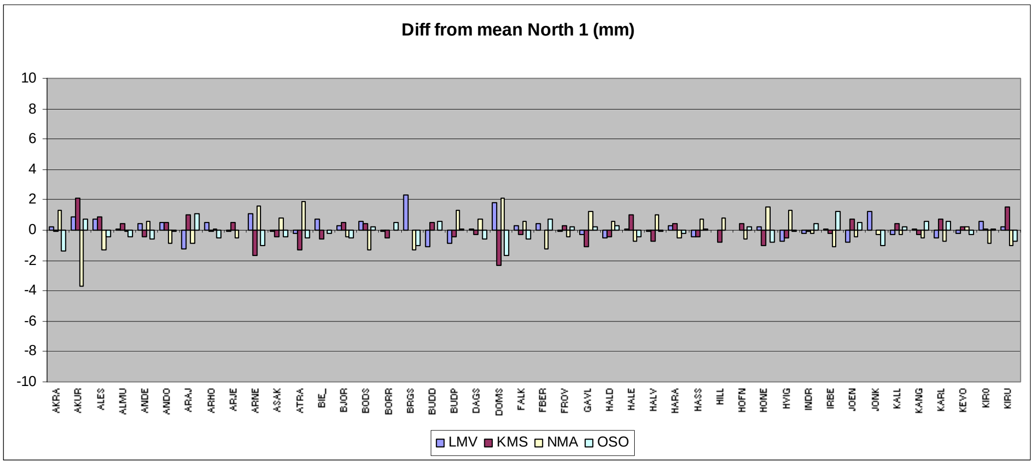
The coordinate set is a snap shot of the stations epoch 2003.75, in fact a very good one. Many of the stations are permanent and are regularly processed by different organizations (but not all stations by the same organization), so a possibility to get more general coordinates would be to combine these solutions. In such a work the snap shot of the NKG 2003 campaign could be very useful for check the consistency between the different solutions.

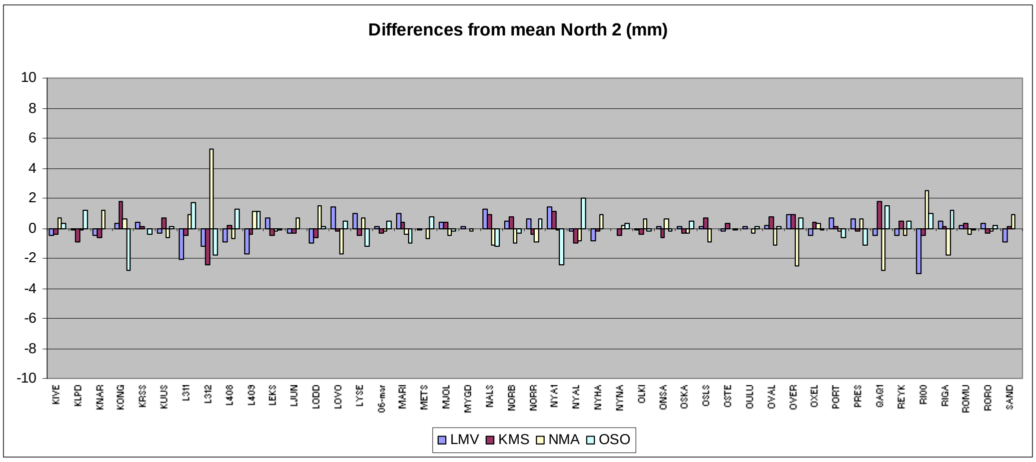
References

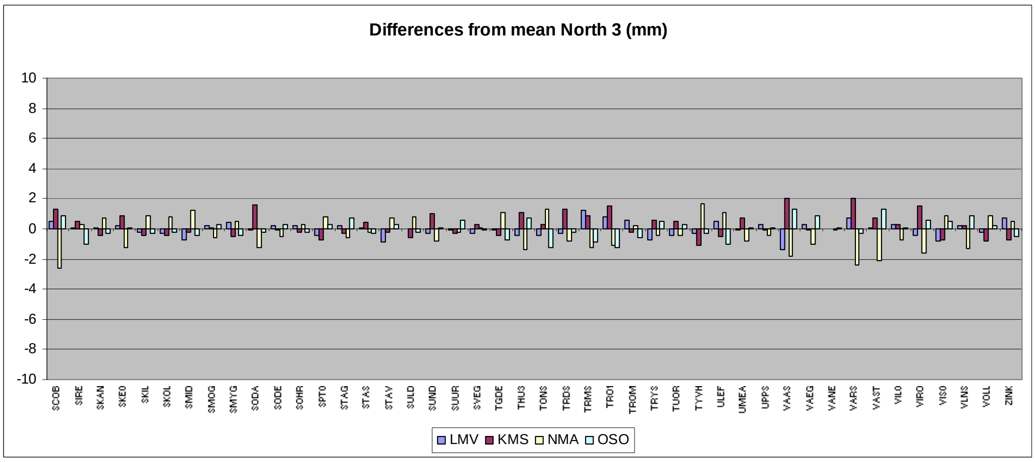
Jivall L & Lidberg M (2000): SWEREF 99 – an updated EUREF realization for Sweden. EUREF, Symposium of the IAG Sub commission for Europe (EUREF), June 22-24 2000, EUREF Publication No. 9, 167-175, Tromsö, Norway.

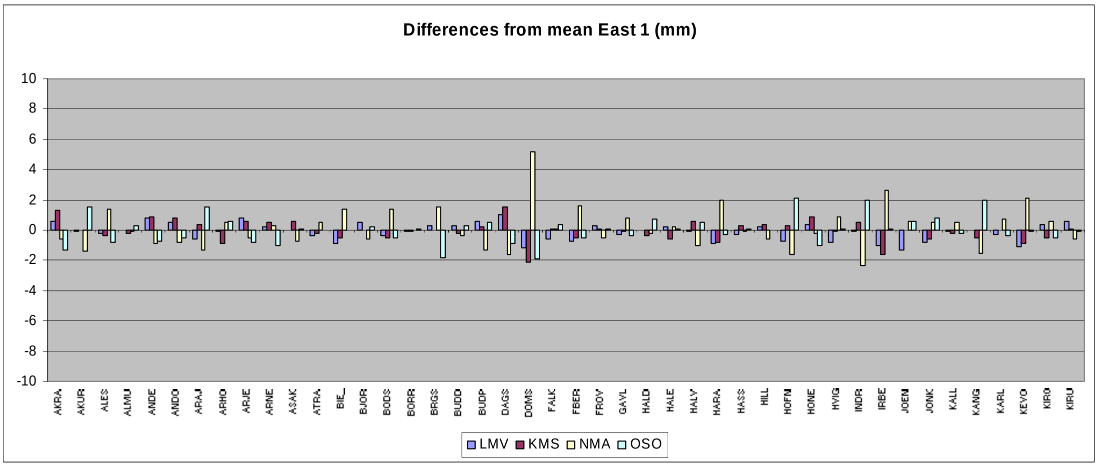
Jivall et al 2005: Processing of the NKG 2003 GPS campaign. LMV-report 2005:7. National Land Survey of Sweden. www.lantmateriet.se.

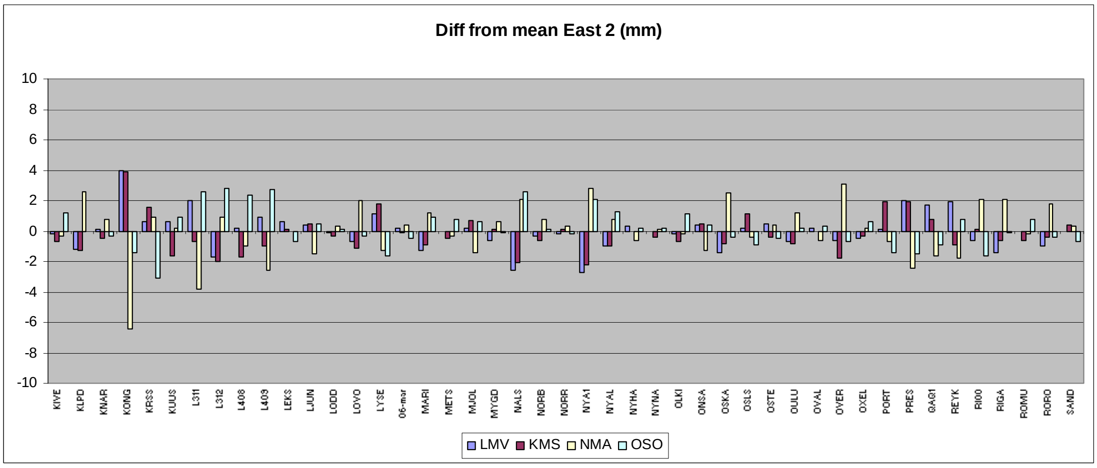
A. Comparison after harmonization

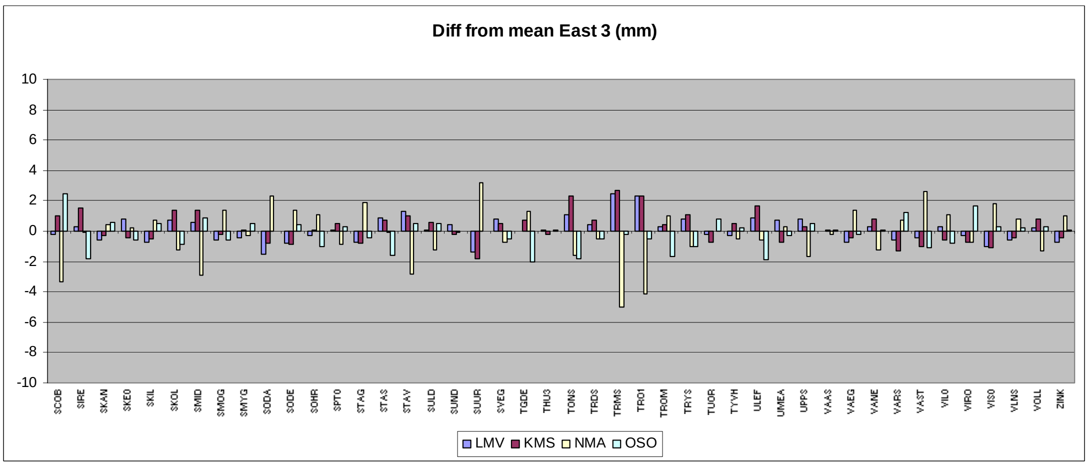







Differences from mean East 1 (mm)
10
8
6
4
2
0
-2
-4
-6
-8
-10
AKRA AKUR ALES ALMU ANDE ANDO ARAJ ARHO ARJE ARNE ASAK ATRA BIE_ BJOR BODS BORR BRGS BUDD BUDP DAGS DOMS FALK FBER FROY GAVL HALD HALE HALV HARA HASS HILL HOFN HONE HVIG INDR IRBE JOEN JONK KALL KANG KARL KEVO KIR0 KIRU
LMV KMS NMA OSO


Diff from mean East 2 (mm)
10
8
6
4
2
0
-2
-4
-6
-8
-10
KIVE KLPD KNAR KONG KRSS KUUS L311 L312 L408 L409 LEKS LJUN LODD LOVO LYSE 06-mar MARI METS MJOL MYGD NALS NORB NORR NYA1 NYAL NYHA NYNA OLKI ONSA OSKA OSLS OSTE OULU OVAL OVER OXEL PORT PRES QAQ1 REYK RI00 RIGA ROMU RORO SAND
LMV KMS NMA OSO


Diff from mean East 3 (mm)
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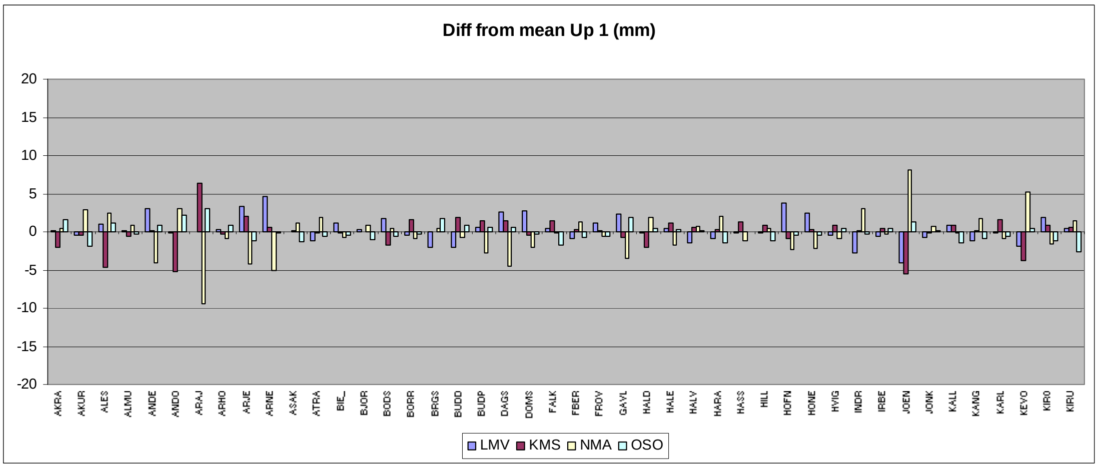
SCOB SIRE SKAN SKE0 SKIL SKOL SMID SMOG SMYG SODA SODE SOHR SPT0 STAG STAS STAV SULD SUND SUUR SVEG TGDE THU3 TONS TRDS TRMS TRO1 TROM TRYS TUOR TYVH ULEF UMEA UPPS VAAS VAEG VANE VARS VAST VIL0 VIRO VIS0 VLNS VOLL ZINK
LMV KMS NMA OSO


Diff from mean Up 1 (mm)
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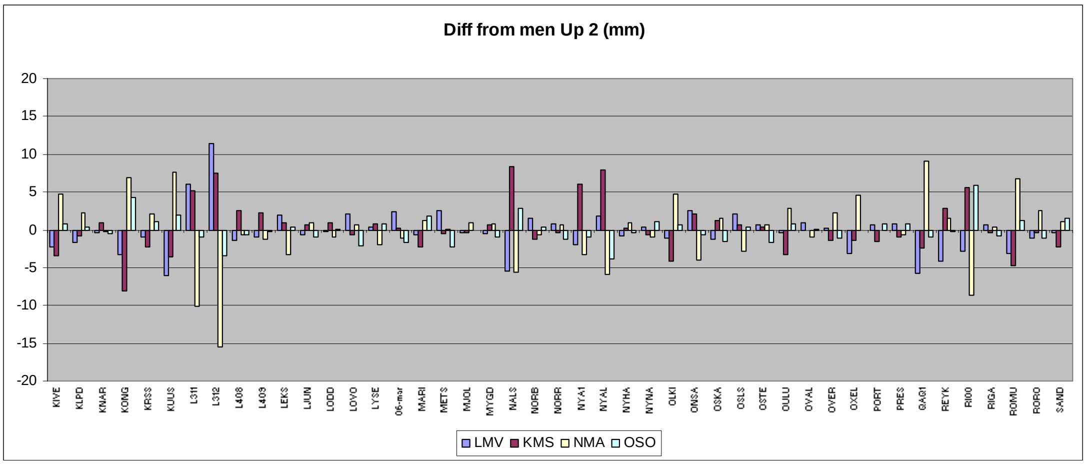
AKRA AKUR ALES ALMU ANDE ANDO ARAJ ARHO ARJE ARNE ASAK ATRA BIE_ BJOR BODS BORR BRGS BUDD BUDP DAGS DOMS FALK FBER FROY GAVL HALD HALE HALV HARA HASS HILL HOFN HONE HVIG INDR IRBE JOEN JONK KALL KANG KARL KEVO KIR0 KIRU
LMV KMS NMA OSO


Diff from men Up 2 (mm)
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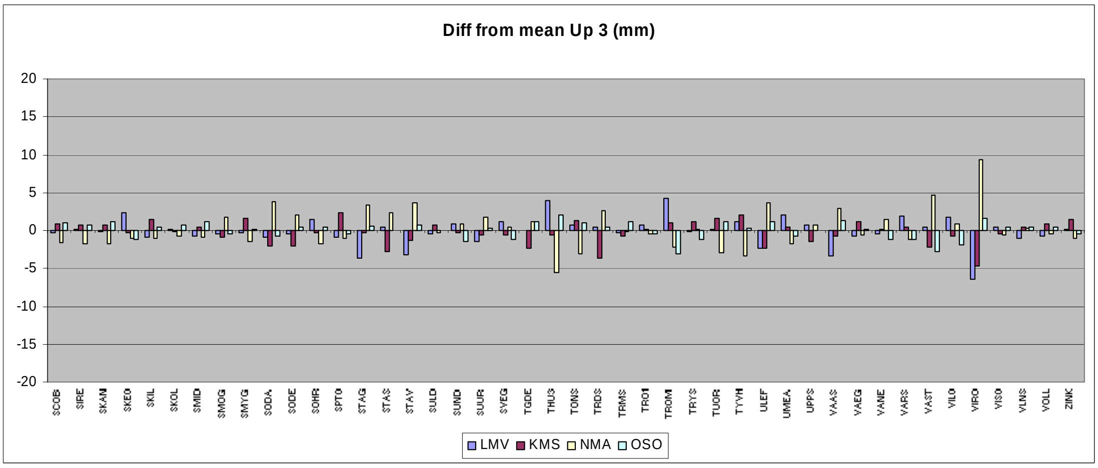
LMV KMS NMA OSO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SCOB SIRE SKAN SKE0 SKIL SKOL SMID SMOG SMYG SODA SODE SOHR SPT0 STAG STAS STAV SULD SUND SUUR SVEG TGDE THU3 TONS TRDS TRMS TRO1 TROM TRYS TUOR TYVH ULEF UMEA UPPS VAAS VAEG VANE VARS VAST VIL0 VIRO VIS0 VLNS VOLL ZINK
LMV KMS NMA OSO

B. Final combined coordinates in ITRF2000 epoch 2003.75

Station	X	Y	Z	Latitude			Longitude			h
AKRA	3254758.5874	295601.6128	5458918.8409	59	15	40.162546	5	11	21.997171	65.1172
AKUR	2502918.5717	-819166.9627	5789714.8936	65	41	7.527077	-18	7	20.928177	134.1588
ALES	2938027.3479	319096.3493	5633413.9555	62	28	34.980641	6	11	54.757201	189.8870
ALMU	3051686.9263	995723.6848	5493062.9845	59	51	58.665284	18	4	14.865394	56.6094
ANDE	2169480.9148	627616.8718	5944952.2349	69	19	33.806299	16	8	5.338510	44.2585
ANDO	2175764.8320	624247.8976	5943414.8317	69	16	42.143599	16	0	31.303832	410.6163
ARAJ	3277266.5876	1309685.8298	5295146.7568	56	29	36.592344	21	46	58.828475	208.5641
ARHO	3033319.5435	1051907.2736	5492748.4149	59	51	39.296362	19	7	32.655022	40.8546
ARJE	2441775.1562	799268.1815	5818729.3538	66	19	4.865846	18	7	29.513638	489.2236
ARNE	3121952.5970	633902.4445	5507296.4802	60	7	10.456920	11	28	39.675335	196.6044
ASAK	3286466.4641	723964.3668	5400051.7214	58	14	30.163506	12	25	23.080325	112.6673
ATRA	3382554.0630	777774.8477	5333332.8494	57	7	13.633050	12	56	57.640053	165.3756
BIE_	3154144.2738	917058.8568	5449043.1160	59	5	15.913277	16	12	41.923532	91.6453
BJOR	3169460.3481	805521.4644	5457845.8620	59	14	25.049725	14	15	35.523083	199.4249
BODS	2393811.6263	612747.7349	5860377.6599	67	16	30.158486	14	21	28.109270	50.8152
BORR	3523674.9150	928375.9673	5217378.7300	55	14	57.216280	14	45	36.663776	158.9460
BRGS	3155871.1642	290902.8634	5516573.5590	60	17	19.481129	5	15	59.563128	93.8190
BUDD	3513649.3528	778954.7377	5248201.9529	55	44	19.926687	12	29	59.856187	87.9557
BUDP	3513638.2818	778956.3810	5248216.4219	55	44	20.469399	12	30	0.085468	94.0294
DAGS	3122524.3628	466764.2060	5524286.5581	60	25	0.590496	8	30	6.449291	845.3651
DOMS	2957499.2597	474477.2292	5612998.1331	62	4	24.187291	9	6	51.853410	733.3466
FALK	3278189.6828	790418.5431	5395964.7976	58	10	11.776130	13	33	21.915732	259.9188
FBER	3408401.3181	755024.5572	5320097.1446	56	54	12.838713	12	29	25.399943	63.7055
FROV	3132396.4978	860615.4634	5470596.9011	59	27	59.749437	15	21	45.919430	83.0049
GAVL	2993586.6966	922761.7340	5537295.8504	60	40	0.409089	17	7	54.176227	55.3864
HALD	3216858.5498	647832.1092	5450991.3868	59	7	20.131135	11	23	10.683985	62.0599
HALE	3115217.6604	806835.8348	5488628.1283	59	47	3.675953	14	31	13.583395	234.5759
HALV	3456798.7196	906264.1963	5265352.9450	56	0	49.187975	14	41	25.945657	72.5524
HARA	3414100.0473	880514.9557	5297435.7386	56	31	50.548889	14	27	42.293419	211.8560
HASS	3464655.5746	845750.1366	5270271.6918	56	5	31.982963	13	43	5.076671	114.0576
HILL	3351528.4856	828634.3617	5345223.3891	57	19	1.178683	13	53	14.468955	212.4473
HOFN	2679689.9926	-727951.2438	5722789.2884	64	16	2.250331	-15	11	52.515360	82.6959
HONE	3132537.3405	566401.9816	5508615.1977	60	8	36.869260	10	14	56.617715	181.4228
HVIG	3523228.6414	502878.8676	5275213.1004	56	10	21.095560	8	7	23.151878	63.7218
INDR	3177703.5301	1662050.1151	5257080.3777	55	52	44.782764	27	36	40.107893	213.6405
IRBE	3183612.0641	1276706.6593	5359310.8632	57	33	15.905960	21	51	7.193165	40.6878
JOEN	2564139.1129	1486149.7560	5628951.4318	62	23	28.223771	30	5	46.169334	113.7375
JONK	3309991.5798	828932.2615	5370882.4564	57	44	43.705214	14	3	34.593751	260.4011
KALL	3237443.3561	758888.5786	5424620.9530	58	39	49.062907	13	11	33.010548	90.0978
KANG	3078174.9738	1608797.7677	5331767.6517	57	5	40.540959	27	35	37.200148	163.8297
KARL	3160763.0950	759160.3153	5469345.6926	59	26	38.476035	13	30	20.252058	114.3253
KEVO	1972158.1932	1005174.4726	5961798.7967	69	45	21.202191	27	0	25.711923	135.9368
KIR0	2248123.2150	865686.6698	5886425.7662	67	52	39.272419	21	3	36.863379	498.0413
KIRU	2251420.8155	862817.2074	5885476.6924	67	51	26.465067	20	58	6.408414	390.9694
KIVE	2632277.1946	1266957.4282	5651027.7075	62	49	11.544469	25	42	8.141467	216.3162
KLPD	3359228.1678	1297490.4662	5246690.3389	55	42	55.278148	21	7	7.983582	42.7483

KNAR	3431762.5836	812400.2727	5296793.0496	56	31	17.664428	13	19	6.366517	113.9577
KONG	3183811.0452	541144.9938	5481926.0674	59	39	54.535417	9	38	46.484938	227.1250
KRSS	3348185.8605	465041.0271	5390738.2783	58	4	57.701015	7	54	26.705198	147.7625
KUUS	2282711.4838	1267071.8685	5800215.8486	65	54	36.895566	29	2	0.524665	379.0288
L311	3376643.0337	1352769.9641	5221718.8865	55	19	6.745000	21	49	56.307880	92.5089
L312	3320254.0314	1570665.2038	5197158.2262	54	55	51.397915	25	19	0.331053	229.5558
L408	3311606.6354	1453968.8188	5236111.2744	55	32	44.819957	23	42	14.368025	138.3882
L409	3425867.8966	1482315.7191	5154672.4781	54	16	19.523500	23	23	50.379655	228.4209
LEKS	3022572.9212	802945.8092	5540684.1541	60	43	19.722679	14	52	37.228130	478.1607
LJUN	3394252.5769	842398.5075	5316209.5268	56	50	16.314606	13	56	17.744586	196.3137
LODD	3504242.4443	808744.1673	5249934.9603	55	46	0.998333	12	59	44.690783	56.3532
LOVO	3104219.1798	998384.1615	5463290.7027	59	20	16.089503	17	49	44.098099	79.6678
LYSE	3269683.9398	366420.5995	5446037.5801	59	1	56.428671	6	23	39.240264	287.7511
MAR6	2998189.4392	931451.7616	5533398.6671	60	35	42.517043	17	15	30.693975	75.4408
MARI	3121535.1963	967771.3826	5458911.7085	59	15	41.193561	17	13	30.125719	37.8463
METS	2892570.8188	1311843.4328	5512634.1289	60	13	2.899021	24	23	43.151544	94.6198
MJOL	3241110.5949	876032.9902	5404956.8641	58	19	29.257692	15	7	29.815966	159.8037
MYGD	3379477.5810	598261.6074	5358170.5416	57	32	2.783052	10	2	20.186148	127.9848
NALS	1202433.8622	252632.2796	6237772.5829	78	55	46.396648	11	51	55.111702	84.2328
NORB	3068753.8376	875354.2331	5504108.8792	60	3	45.048255	15	55	14.391427	176.1418
NORR	3199093.0510	932231.4694	5420322.6793	58	35	24.833333	16	14	46.977951	40.9732
NYA1	1202433.8628	252632.2800	6237772.5863	78	55	46.396648	11	51	55.111747	84.2362
NYAL	1202430.5512	252626.6990	6237767.6112	78	55	46.504705	11	51	54.309162	78.5111
NYHA	3467557.7777	771271.7438	5279655.2769	56	14	39.356434	12	32	23.575306	63.1279
NYNA	3141747.3916	1017435.9871	5438418.3499	58	54	10.706008	17	56	39.242533	66.0969
OLKI	2863210.0008	1126271.5364	5568267.3953	61	14	22.757464	21	28	21.642601	30.6062
ONSA	3370658.5718	711877.1220	5349786.9410	57	23	43.075111	11	55	31.861171	45.5824
OSKA	3341339.9149	957912.4884	5330003.4077	57	3	56.300787	15	59	48.516623	149.7999
OSLS	3169981.9028	579956.7555	5485936.6695	59	44	11.712092	10	22	3.925258	221.5422
OSTE	2763885.2474	733247.4904	5682653.5420	63	26	34.057623	14	51	29.046746	490.0901
OULU	2423778.4672	1176553.8338	5761861.0191	65	5	11.506317	25	53	34.535813	88.8576
OVAL	3037697.4452	938862.3153	5510711.8425	60	10	58.642316	17	10	29.388550	81.8152
OVER	2368884.7404	994492.3224	5818478.3665	66	19	4.290500	22	46	24.145532	222.9736
OXEL	3177394.3820	977921.6621	5425008.4094	58	40	15.441066	17	6	25.352279	46.8192
PORT	3267084.8120	542580.9987	5432706.2499	58	48	13.928207	9	25	45.600089	63.6883
PRES	3227088.6670	353649.8215	5471909.9041	59	29	18.718022	6	15	14.282232	166.4434
QAQ1	2170942.1348	-2251829.9647	5539988.3259	60	42	54.947521	-46	2	51.944911	110.4130
REYK	2587384.3347	-1043033.5212	5716564.0159	64	8	19.622028	-21	57	19.747985	93.0254
RI00	3183914.0589	1421473.6508	5322796.8693	56	56	54.470984	24	3	30.965538	29.3703
RIGA	3183899.2311	1421478.4814	5322810.7950	56	56	55.030029	24	3	31.584060	34.7321
ROMU	2410839.1841	1388069.6051	5720515.3016	64	13	2.633043	29	55	54.128943	241.7122
RORO	3339312.1912	686422.8320	5372576.0238	57	46	37.037051	11	36	56.925641	51.3375
SAND	3228737.1194	582180.5439	5451381.2483	59	7	44.297174	10	13	16.667687	69.1965
SCOB	1982098.7615	-798842.3819	5989460.9759	70	29	6.843693	-21	57	3.030487	128.6601
SIRE	3323397.4067	336993.7003	5415278.0084	58	30	11.332457	5	47	24.081018	60.7412
SKAN	3537800.6052	807531.9492	5227707.7794	55	24	49.546891	12	51	28.598544	48.5894
SKE0	2534030.9116	975174.5562	5752078.5305	64	52	45.110128	21	2	53.843856	81.2760
SKIL	3511254.6709	893660.5319	5231575.3295	55	28	29.581761	14	16	45.689267	58.1286
SKOL	3187460.1361	543919.0213	5479516.0650	59	37	21.890422	9	41	1.931713	200.8681
SMID	3557911.2557	599176.6633	5242066.4356	55	38	26.322944	9	33	33.500665	122.8327
SMOG	3290543.5591	652615.2074	5406535.5696	58	21	12.471069	11	13	4.539838	45.2410
SMYG	3536512.2937	840549.8098	5223404.0052	55	20	44.521024	13	22	11.464728	50.1424

SODA	2200146.7036	1091638.3381	5866870.7880	67	25	15.093320	26	23	20.585324	299.8229
SODE	2993266.3958	996674.0302	5524712.0255	60	26	14.258303	18	24	58.739357	40.6700
SOHR	3172308.3354	603814.0171	5481968.1359	59	40	1.090794	10	46	36.166100	157.1570
SPT0	3328984.5532	761910.2482	5369033.6743	57	42	53.850377	12	53	28.855826	219.9590
STAG	3629048.0697	603765.6761	5192855.8322	54	51	55.046350	9	26	44.871500	107.8279
STAS	3275753.6501	321111.0210	5445042.0601	59	1	3.762503	5	35	55.045971	104.9091
STAV	3091410.6638	1045979.3692	5461608.2947	59	18	31.907169	18	41	35.729775	35.9610
SULD	3446394.2311	591713.1255	5316383.4430	56	50	30.333334	9	44	31.763396	120.7238
SUND	2838909.6615	903822.2116	5620660.4023	62	13	56.910531	17	39	35.596037	31.8545
SUUR	2959056.4001	1341058.5074	5470427.2905	59	27	48.885841	24	22	48.939380	84.3878
SVEG	2902494.8383	761455.9556	5609859.8784	62	1	2.688705	14	42	0.045826	491.2547
TGDE	3358080.9309	445364.8938	5386152.9195	58	0	22.955296	7	33	17.115036	45.8465
THU3	538093.5751	-1389088.0458	6180979.2342	76	32	13.370874	-68	49	30.128747	36.1128
TONS	3301576.3569	389093.1040	5425120.9079	58	40	18.850932	6	43	16.843288	114.2979
TRDS	2820170.8438	513486.0350	5678935.9228	63	22	16.980735	10	19	8.965119	317.7273
TRMS	2102928.4974	721619.4468	5958196.2416	69	39	45.784765	18	56	22.726281	138.0775
TRO1	2102928.5009	721619.4480	5958196.2509	69	39	45.784757	18	56	22.726281	138.0875
TROM	2102940.2233	721569.4457	5958192.1621	69	39	45.894457	18	56	17.985501	132.4668
TRYS	2987993.8613	655946.2118	5578690.2102	61	25	23.574380	12	22	53.696458	724.8430
TUOR	2917810.7826	1205222.7052	5523550.1084	60	24	57.056722	22	26	36.327098	60.6104
TYVH	3471138.4076	665488.5483	5291632.4792	56	26	16.774424	10	51	11.096034	88.7469
ULEF	3223773.3753	527002.8206	5459933.8030	59	16	41.076115	9	17	3.274375	125.3200
UMEA	2682407.6446	950396.0454	5688993.3082	63	34	41.300247	19	30	34.549591	54.5790
UPPS	3060037.7056	970123.0043	5492999.4098	59	51	54.540651	17	35	24.591261	57.1965
VAAS	2699864.3556	1078263.9918	5658064.8676	62	57	40.295035	21	46	14.289396	58.1255
VAEG	3612854.9835	763382.4428	5183133.8156	54	42	51.926954	11	55	51.201093	60.5552
VANE	3249408.0322	692758.0951	5426397.1326	58	41	35.258530	12	2	6.011876	169.7226
VARS	1844607.3153	1109719.1996	5983936.1431	70	20	10.942448	31	1	52.299045	174.8800
VAST	3097214.7217	921046.1324	5480693.5904	59	38	44.457217	16	33	40.910815	68.5528
VIL0	2620258.6177	779138.1343	5743799.4697	64	41	52.250636	16	33	35.750977	450.0173
VIRO	2788248.1976	1454873.4666	5530280.1810	60	32	19.682937	27	33	17.987572	36.9750
VIS0	3246470.2796	1077900.4966	5365278.0866	57	39	13.931083	18	22	2.340221	79.8217
VLNS	3343600.6532	1580417.7287	5179337.2871	54	39	11.313802	25	17	55.206790	240.8501
VOLL	3498678.0362	858203.7287	5245922.9922	55	42	6.565192	13	46	55.830832	141.3360
ZINK	3196313.2901	861751.7063	5433743.3811	58	49	9.704703	15	5	19.105467	231.2861

Transformation from a Common Nordic Reference Frame to ETRS89 in Denmark, Finland, Norway, and Sweden – status report

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Abstract

The Nordic countries have implemented national realizations of ETRS89. Depending on when the realizations were made and on which ITRF the realizations are based, there are differences between the realizations up to a few cm. The national realizations have already been introduced to the users and will not be replaced. In this paper we present the transformations from the new developed common Nordic reference frame, NKG_RF03, to the official national ETRS89 realizations. The transformation is performed in two steps. First step is to correct for intraplate deformations using a new developed three dimensional velocity model, NKG_RF03vel. Second step is to perform a seven parameter transformation for each nation.

1. Introduction

The Nordic countries have implemented national realisations of the ETRS89. Depending on when the realizations were made and which ITRF the realization are based on, there are differences between the realizations of up to a few cm. The national realizations have already been introduced to the users and will not be replaced. There are however situations were a common reference frame could be useful, e.g. for the Nordic Positioning Service which is under development (Engen and Jonsson, 2000). A common reference frame could also act as a link for transformations between the different national realizations, or between the national realizations and ITRF.

Resolution No 3 of the 14th General Meeting of the Nordic Geodetic Commission (NKG) in Finland, 2002, “recommends the development of a unified ETRS89 reference frame on the cm level for the Nordic area and of formulas for the transformation from such a reference frame to the national realizations of ETRS89, as well as the transformation from ITRF to the unified ETRS89 reference frame”. The NKG Working Group for Positioning and Reference frames was given the task to develop such a common Nordic reference frame and transformation formulas. The chairman of this working group, Per Knudsen, DNSC, has been leading the activity.

There have been three sub-projects:

- Organizing the campaign and quality check of the data lead by Bo Madsen.
- Processing lead by Lotti Jivall, Report: Processing of the NKG 2003 GPS Campaign. Gävle 2005
- Transformations lead by Torbjørn Nørbech, Report: “Transformation from a Common Nordic Reference Frame to ETRF89 in Denmark, Finland, Norway, and Sweden.” (to be published)

2. The general strategy

For the development of a common Nordic reference frame on the cm level, the NKG 2003 GPS Campaign was observed and analysed (Jivall et al. 2006). The resulting coordinate set from the campaign have been denoted NKG_RF03 (NKG reference frame 2003).

As a "unified ETRS89 reference frame on the cm level" we propose to use the realization of ITRF2000 at the reference epoch 2003.75 which is the reference epoch for the GPS campaign. We understand that the intention of the NKG resolution no 3 may have been to establish a new frame with a set of coordinate close to each Nations individual realization. We found however early in our discussions that such a frame could cause confusion and misunderstanding. The NKG_RF03 is therefore presented in ITRF2003, epoch 2003.75.

A transformation from ITRF2000 epoch 2003.75 to the individual national ETRS89 realizations could be performed in some different ways. In general we have to know the velocity of each station. In the Nordic area it is not sufficient to use a general velocity model (e.g. Nuvel) for transformations with geodetic accuracy. The Glacial Isostatic Adjustment (GIA) process in our region causes motions which are not taken into account in plate tectonic motion models like Nuvel1A or by the ITRF2000 rotation pole for Eurasia. These GIA motions are deforming the crust and can not be absorbed with a so called rigid plate motion model. This post glacial rebound process causes relative motions up to 3 mm in the horizontal directions and 11 mm in the vertical direction. These relative motions are called intraplate deformations and are defined relative to a stable tectonic plate.

Therefore the transformations have to be split up into two parts. The first part is to correct for intraplate deformations and the second part to correct for the rigid motion (primarily caused by the plate tectonic motion).

When the Nordic countries performed their ETRS89 realizations they did not apply correction for intraplate deformations. The main reason for not doing so was that this deformation was not known with sufficient accuracy at that time. The corrections for intraplate deformations should therefore be performed for the period from epoch 2003.75 and back only to the reference epoch of each nations ETRS89 realization. This is because the purpose of this transformation is to hit each nations ETRS89 realization and not the "true" ETRS89.

In the second part we have merged the rigid plate motion (three rotation parameters) with a 7-parameter Helmert transformation to adjust for systematic and stochastic differences in the reference frame realizations. The resulting 7-parameter transformation thus includes the rigid plate motion, the transformation from ITRF2000 to ETRS89, and contribution from differences in the reference frame realizations. Thus, there will be an individual set of 7 transformation parameters for each country.

For applications which require less accuracy it could of course be possible to simplify the transformation by omitting the intraplate corrections and/or to use a common 7-parameter transformation for all the nations. It has however not been the scope of this work to develop such parameters.

3. Transformation from ITRF2000 epoch 2003.75 to the national ETRS89 realizations

The transformation from ITRF2000 epoch 2003.73 to the individual official national realizations of the ETRS89 is performed in two steps. Equation (1) is removing the intraplate deformations, and in equation (2) a 7-parameter transformation is performed:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{t_r}^{ITRF2000} = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{2003.75}^{ITRF2000} + (t_r - 2003.75) \begin{pmatrix} V_{X_{intra}} \\ V_{Y_{intra}} \\ V_{Z_{intra}} \end{pmatrix}_{NKG\_RF03vel}^{ITRF2000} \qquad (1)$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}^{national\_ETRS89} = \begin{pmatrix} T_X \\ T_Y \\ T_Z \end{pmatrix} + (1+D) \begin{pmatrix} 1 & R_Z & -R_Y \\ -R_Z & 1 & R_X \\ R_Y & -R_X & 1 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{t_r}^{ITRF2000} \qquad (2)$$

Here X, Y, Z are geocentric coordinates. $V_{x\text{-}intra}$, $V_{Y\text{-}intra}$, $V_{Z\text{-}intra}$ are the intraplate velocities. t_r is the reference epoch of the ETRS89 realisation. The superscript and subscripts outside the coordinate vectors means reference frame and reference year (reference epoch) respectively.

For the intraplate velocities we use the NKG_RF03vel velocity model. This model is described in Appendix B.

The transformation parameters for each nation have been computed independently at five institutions (DNSC, FGI, LMV, NMA, and OSO) and compared. The different solutions show differences in the estimated parameters. In the coordinate domain, the contributions from single transformation parameters are of magnitude +/- 0.7 mm. The DNSC solution is more unlike the FGI, LMV, NMA, and OSO solutions. De differences between these four solutions are of the magnitude +/- 0.3 mm. The reason for these differences may be that some institutions use full rotation matrix and other linearized formulas (using the assumptions: COS(A)=1 and SIN(A)=A for small A). The reasons may also be the number of decimals used, especially on the reference epoch. A round off error in the first decimal of the year may cause an error of the magnitude we here are speaking of. However, if the complete sets of transformation parameters from the different solutions are compared, the differences in transformed "fitting points" show a maximum discrepancy of 0.2 mm in some few points. Most of the points show discrepancies of 0.0 mm or 0.1 mm.

The set of final combined transformation parameters is shown in Table 1 below.

Tab 1. *Transformation parameters from ITRF2000 epoch 2003.75 to each national official realization of ETRS89 after reduction for intraplate deformations.*

Nation	t_r	T_x(cm)	T_y(cm)	T_z(cm)	D(ppb)	R_x(mas)	R_y(mas)	R_z(mas)
Denmark	1994.707	-3.31	55.84	2.24	-10.91	-16.732	-11.308	18.998
Finland	1997.000	11.15	-7.78	-13.81	9.84	0.700	-4.710	8.091
Norway	1994.665	-5.36	-11.10	-4.58	8.31	3.099	-10.295	8.912
Sweden	1999.500	3.44	3.03	-6.79	0.08	-2.134	-7.765	9.810

Tab 2. *Number of fitting points and standard errors of unit weight,* s_{north}, s_{east}, s_{up}

Nation	fitting points	s_{north} (mm)	S_{east} (mm)	S_{up} (mm)
Denmark	6	2.0	1.5	1.1
Finland	12	1.6	1.5	3.2
Norway	9	3.6	3.9	10.0
Sweden	36	1.9	1.4	3.3

(Note the signs of the rotations used in equation 2. Other conventions for signs in rotation matrixes may be used elsewhere. However, the convention used in equation 2 and the signs of the parameters in Table 1 are consistent.)

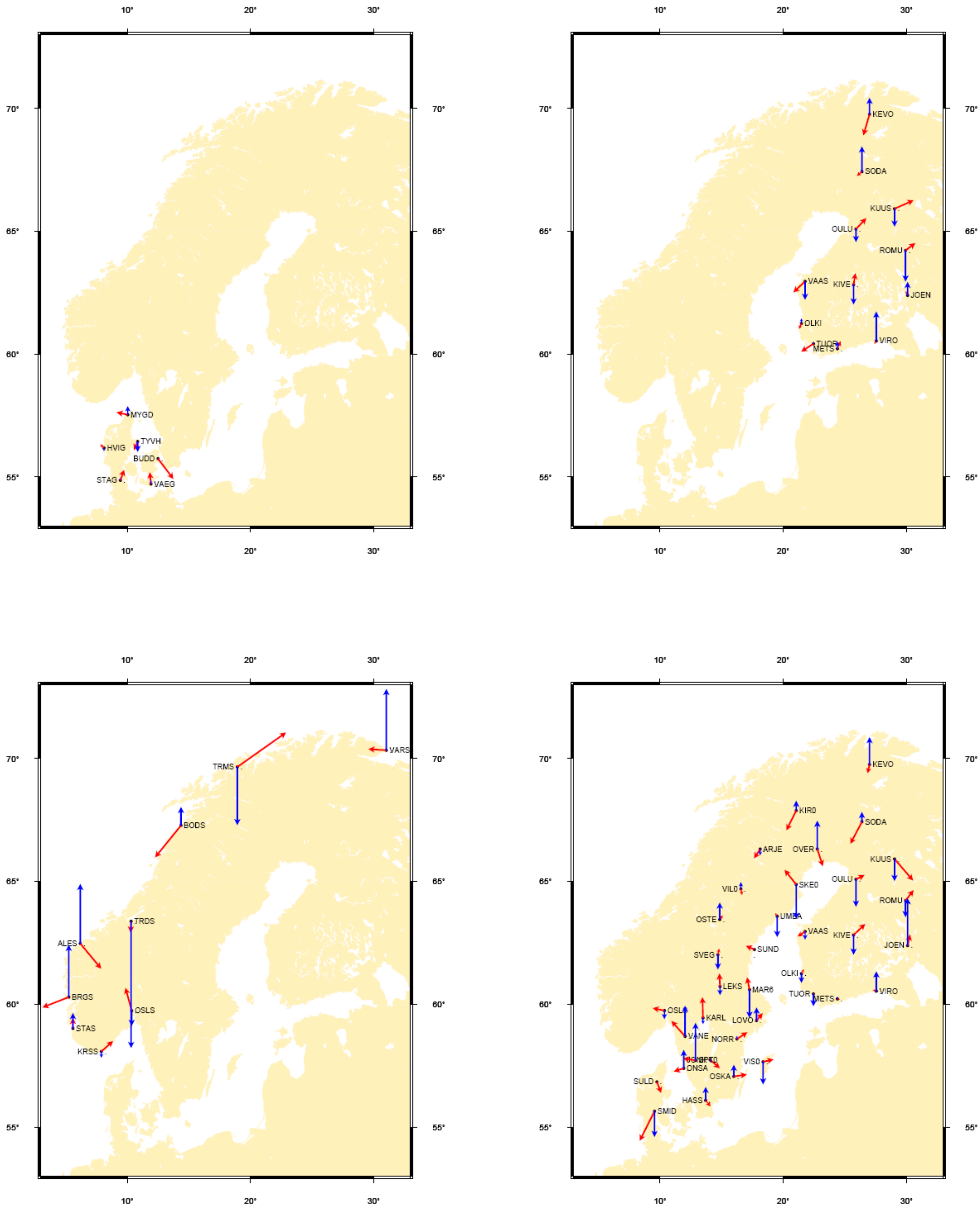

Fig 1. *The arrows show residuals after transformations for each country. Red arrow shows the horizontal components and blue arrow shows the vertical component. Arrow scale is 1:1.*

4. Transformation from ITRF2000 current epoch to NKG_RF03 (in ITRF2000 epoch 2003.75)

The situation of interest here is a when some work has been performed in ITRF2000 “current epoch”, and the result should be presented in NKG_RF03, which is in ITRF2000 epoch 2003.75. (For future work possibly based on the new ITRF2005, some improved method must be utilised. The development of such methodology will be the task for future work within the NKG Working Group for Positioning and Reference Frames.)

The task is thus to convert from ITRF2000 “current epoch”, t_c, to epoch 2003.75. To do so, booth the plate tectonic motion as well as the intraplate deformation must be corrected for. The combined correction is given by equation 3, and the corrected coordinates are given by equation 4 below:

$$\begin{pmatrix} dX \\ dY \\ dZ \end{pmatrix}^{ITRF2000}_{2003.75-t_c} = (2003.75 - t_c) \begin{pmatrix} 0 & -\dot{R}_3 & \dot{R}_2 \\ \dot{R}_3 & 0 & -\dot{R}_1 \\ -\dot{R}_2 & \dot{R}_1 & 0 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}^{ITRF2000}_{t_c} + (2003.75 - t_c) \begin{pmatrix} V_{X_{intra}} \\ V_{Y_{intra}} \\ V_{Z_{intra}} \end{pmatrix}^{ITRF2000}_{NKG\_RF03vel} \tag{3}$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}^{ITRF2000}_{2003.75} = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}^{ITRF2000}_{t_c} + \begin{pmatrix} dX \\ dY \\ dZ \end{pmatrix}^{ITRF2000}_{2003.75-t_c} \tag{4}$$

In the first part of eq. 3, the plate tectonic motion is corrected for using a rigid plate rotation. Here we have followed the formulas and conventions from Altamimi et al. (2003). The rotation velocities $(\dot{R}_1 \quad \dot{R}_2 \quad \dot{R}_3)$ are the ITRF2000 rotation pole for Eurasia which is again given in Altamimi et al (2003) as (-0.081, -0.489, 0.792) milliarcsecond/year (which must be converted to radians/year before use in eq. 3). (Note the reversed signs for the rotations given in Boucher and Altamimi (2001)). In the second part of eq. 3, the intraplate deformations are corrected for. Pictures on the plate tectonic motion and the intraplate velocities are given in Figure 2 below.

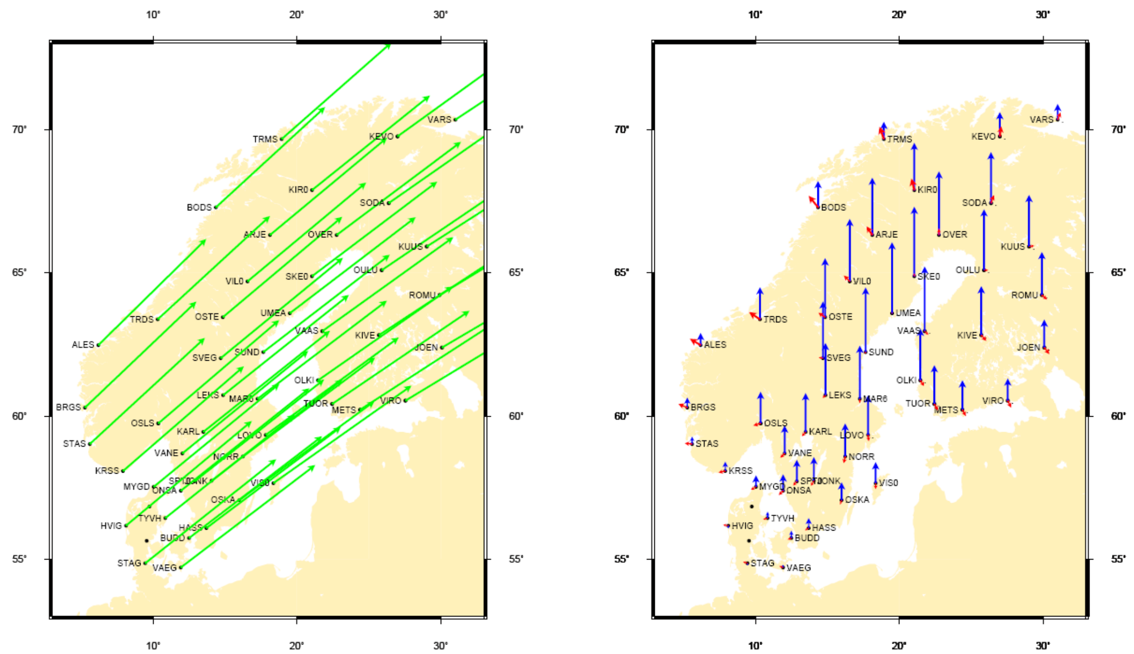

Fig 2. *The figure to the left shows the (horizontal) plate tectonic motion in (mm/yr) according to the ITRF2000 Euler pole for Eurasia. To the right shows the intraplate deformations according to the NKG_RF03 velocity model which is relative to the stable Eurasia tectonic plate as defined by the ITRF2000 rotation pole for Eurasia. The red arrows show the horizontal velocities, and the blue arrows show the vertical velocity (with respect to the earth centre of mass) also in (mm/yr). Arrow scale is 1:1.*

5. Conclusions

The background to the here presented work was the recognized need for a common Nordic reference frame “on the 1 cm level”, together with transformations between such a reference frame and the national realizations of ETRS89.

In order to fulfil the task, the NKG 2003 GPS campaign was observed and analyzed (Jivall et al., 2006). As a "unified ETRS89 reference frame on the cm level for the Nordic area" we propose to use the realization of ITR2000 at epoch 2003.75, which is the reference epoch for the observations. The resulting coordinate set is denoted NKG_RF03. Thus we propose not to develop a common Nordic ETRS89 realization out of NKG_RF03.

Formulas for transformations from NKG_RF03 to the national realizations of ETRS89 have been developed. These are individual transformations for each nation, performed in two steps. The first step is to correct for intra plate deformations for the period from epoch 2003.75 back to each nation's reference epoch for the ETRS89 realization. For this, the NKG_RF03vel model has been compiled and implemented. In the second step is a 7-parameter Helmert transformation applied. The magnitude of the residuals from these transformations is in general at the level of some few mm.

For the implementation and use of NKG_RF03, a procedure for transformation from ITRF2000 “current epoch” to ITRF2000 epoch 2003.75 has been presented. It may however be noted that these transformations may and should be further developed when ITRF2005 are released. We will also stress that the model for intraplate deformations should be improved continuously in order to sufficiently well absorb deformation velocities at time spans of increasing length.

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Appendix A: Example of transformed points

Below is given examples of points that may be used to verify the implementation of the transformations presented above. For each country are given two points in NKG_RF03:

- first in ITRF2000 epoch 2003.75,
- then corrected for intraplate deformations to internal deformation epoch equal to the epoch for the national realisation of ETRS89 (but still in plate tectonic epoch 2003.75),
- and finally after the nation-specific 7-parameter Helmert transformation.

All positions are given in meters in the geocentric (X, Y, Z) frame.

Denmark

NKG_RF03 in ITRF2000, ep 2003.75:

```
MYGD  3379477.5810   598261.6074  5358170.5416
VAEG  3612854.9835   763382.4428  5183133.8156
```

NKG_RF03 in ITRF2000, ep 2003.75, internal deformation epoch 1994.707 (1994-09-15):

```
MYGD  3379477.5692   598261.6119  5358170.5316
VAEG  3612854.9817   763382.4473  5183133.8120
```

NKG_RF03 in ITRF2000, ep 2003.75, internal deformation epoch 1994.707, transformed to official ETRS89 in Denmark with a 7-parameter Helmert transformation using the above presented parameters:

```
MYGD  3379477.8481   598261.4179  5358170.3588
VAEG  3612855.2637   763382.2442  5183133.6417
```

Finland

NKG_RF03 in ITRF2000, ep 2003.75:

```
KEVO  1972158.1932  1005174.4726  5961798.7967
TUOR  2917810.7826  1205222.7052  5523550.1084
```

NKG_RF03 in ITRF2000, ep 2003.75, internal deformation epoch 1997.0:

```
KEVO  1972158.1946  1005174.4719  5961798.7717
TUOR  2917810.7623  1205222.6930  5523550.0800
```

NKG_RF03 in ITRF2000, ep 2003.75, internal deformation epoch 1997.0, transformed to official ETRS89 in Finland with a 7-parameter Helmert transformation using the above presented parameters:

```
KEVO  1972158.5010  1005174.3469  5961798.6439
TUOR  2917811.0759  1205222.5314  5523549.9257
```

Norway

NKG_RF03 in ITRF2000, ep 2003.75:

```
KRSS  3348185.8605   465041.0271  5390738.2783
TRMS  2102928.4974   721619.4468  5958196.2416
```

NKG_RF03 in ITRF2000, ep 2003.75, internal deformation epoch 1994.665:

```
KRSS  3348185.8514   465041.0344  5390738.2692
TRMS  2102928.5019   721619.4541  5958196.2162
```

NKG_RF03 in ITRF2000, ep 2003.75, internal deformation epoch 1994.665, transformed to official ETRS89 in Norway with a 7-parameter Helmert transformation using the above presented parameters:

```
KRSS  3348186.1148   465040.8634  5390738.0940
TRMS  2102928.7943   721619.3477  5958196.1041
```

Sweden

NKG_RF03 in ITRF2000, ep 2003.75:

```
HASS  3464655.5746   845750.1366  5270271.6918
KIR0  2248123.2150   865686.6698  5886425.7662
```

NKG_RF03 in ITRF2000, ep 2003.75, internal deformation epoch 1999.5:

```
HASS  3464655.5699   845750.1374  5270271.6875
KIR0  2248123.2103   865686.6698  5886425.7377
```

NKG_RF03 in ITRF2000, ep 2003.75, internal deformation epoch 1999. 5, transformed to official ETRS89 in Sweden with a 7-parameter Helmert transformation using the above presented parameters:

```
KIR0  2248123.5077   865686.5323  5886425.5946
HASS  3464655.8432   845749.9485  5270271.4983
```

Appendix B: The NKG_RF03vel velocity model

The NKG_RF03vel velocity model covers the area (53° - 73° north, and 0° - 40° east), and describe intraplate deformation velocities with respect to the stable Eurasia tectonic plate. The horizontal and vertical velocities are shown in Figure 5 and Figure 6 respectively.

The model has been compiled within the NKG Working Group for Positioning and Reference Frames during spring 2006. It is available as grid files in the Gravsoft *.gri format (which is commonly used for geoid models). The models consist of the four files:

- NKG_RF03vel.readme
- NKG_RF03vel_n.gri
- NKG_RF03vel_e.gri
- NKG_RF03vel_u.gri

Where the "readme" file describe the model and how it should be used. The three following files contain the intraplate velocities in the north, east and vertical directions respectively. These files will soon be put into the public domain.

The north and east components originate from the GIA model developed within the framework of the BIFROST effort (Baseline Inferencies for Fennoscandian Rebound Observations Sea level and Tectonics) and presented in

Milne et al. (2001). The velocity field from this model has been transformed (rotated) to the GPS-derived velocity field in (Lidberg et al. 2006). Thus, the horizontal velocity field (north and east) describes horizontal displacements relative to stable Eurasia as defined by the ITRF2000 and its rotation pole for Eurasia (Lidberg and Johansson 2005).

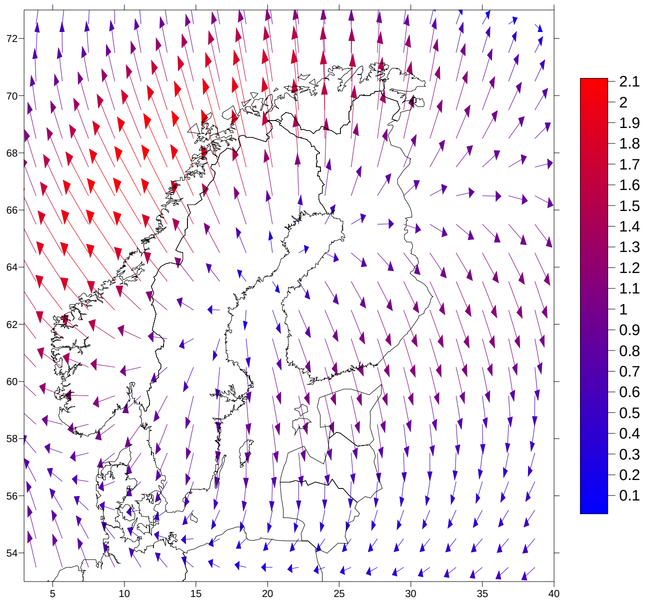

Fig 5. *Horizontal intraplate deformation velocities according to the NKG_RF03vel velocity model. See text. Units: mm/yr.*

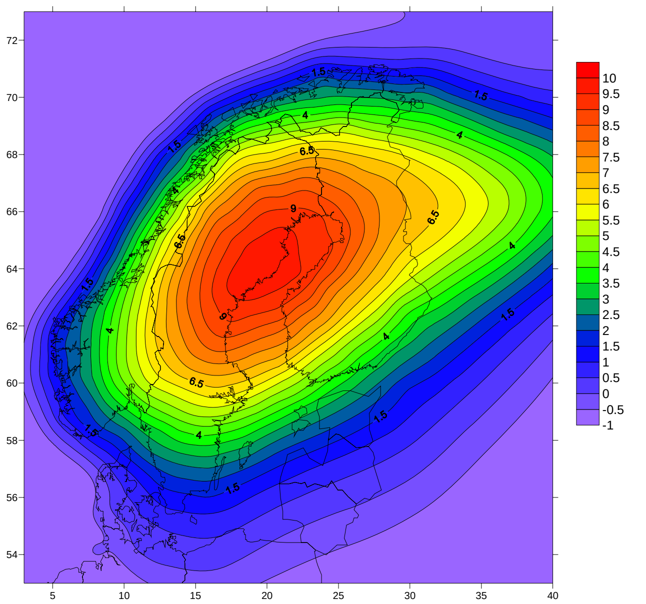

Fig 6. *Vertical velocities according to the NKG_RF03vel velocity model. See text. Units: mm/yr.*

For the up component, the **NKG2005LU**(ABS) model, developed within the NKG Working Group for Height Determination, has been used. This model origins from the NKG2005LU(APP) model (Ågren and Svensson, 2006), which is a smoothed version of a combination of the Vestøl model (Vestøl 2006) used in the Fennoscandia area, and the model from Lambeck (Lambeck et al. 1998 a and b) used in the Baltic and central European area. The apparent land uplift values in NKG2005LU(APP) have been converted from apparent land uplift values to absolute land uplift with the following formula:

$$u_{abs} = (u_{app} + 1.32 \text{ mm})*1.06$$

, where u_{abs} is absolute land uplift relative the earth centre of mass, u_{app} is apparent land uplift from NKG2005LU(APP), and the constant 1.32 mm reflects the absolute sea level rise (for this area of the globe) and the factor 1.06 reflects the geoid rise (Scherneck et al., 2003).

Appendix C: Conversion of intraplate velocities from the $(\dot{n} \quad \dot{e} \quad \dot{u})$ to the $(\dot{X} \quad \dot{Y} \quad \dot{Z})$ frame

To use the velocities from the NKG_RF03vel model in the transformations described in section 2 and 4, the velocities must first be converted from the (north, east, up) frame to the (X, Y, Z) frame. The formulas for this conversion presented below are taken from Hofmann.Wellenhof et al (2001) section 10.2.2, with slight modifications:

$$\begin{cases} \dot{X} = \dfrac{-Z}{R}\dfrac{X}{P}\dot{n} + \dfrac{-Y}{P}\dot{e} + \dfrac{X}{R}\dot{u} \\ \dot{Y} = \dfrac{-Z}{R}\dfrac{Y}{P}\dot{n} + \dfrac{X}{P}\dot{e} + \dfrac{Y}{R}\dot{u} \\ \dot{Z} = \dfrac{P}{R}\dot{n} + \dfrac{Z}{R}\dot{u} \end{cases} \tag{5}$$

Here $R = \sqrt{X^2 + Y^2 + Z^2}$, and $P = \sqrt{X^2 + Y^2}$. Then we have made the approximation assuming a spherical earth. Therefore:

$$\begin{cases} \cos\varphi = P / R \\ \sin\varphi = Z / R \\ \cos\lambda = X / P \\ \sin\lambda = Y / P \end{cases} \tag{6}$$

And here φ is the latitude and λ is the longitude of the site.

Nordic Positioning Service - A summary of the project this far

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Abstract

Nordic Positioning Service is a collobaration project between Denmark, Norway and Sweden for establishment and use of networks of permanent GNSS reference stations.

Two major purposes of Nordic Positioning Service are to exchange data between the networks of permanent reference stations in Denmark, Norway and Sweden and to establish common Positioning Services. To make those visions come true, communication lines has been established between the three control centres. Four Norwegian stations are about to be included in the Swedish Network RTK service, “SWEPOS Network RTK service”, and seven Swedish stations are about to be included in the Norwegian Network RTK service, “CPOS”. Another major purpose is the exchange of knowledge in the field of operation and applications of networks of permanent reference stations.

The presentation shows the achieved results so far and gives an overview of the future development.

Background

In February, 1999 NKG obtained a task from the Directors General to develop a plan for the establishment of a Nordic Positioning Service. In January 2000, a proposal for a two years development project on a Nordic Positioning Service was presented for the Directors General. The proposal was approved and an agreement, which includes external funds, was signed by the Directors General in the fall 2000. An application for the required external funds was submitted to the Nordic Council, but the Council didn’t award any funds.

The development project Nordic Positioning Service is run and co-ordinated by NKG. It was established in 2000 on behalf of the NKG Presidium. The project is managed by a steering committee, which during the years has consisted of 2-3 persons from each Nordic mapping authority, excluding Finland and Iceland who already at the start chose not to take an active part.

The purposes of the project Nordic Positioning Service are:

- Exchange of data: See below.
- Exchange of knowledge and information: In this sense the project has accomplished a lot and it has also contributed to much improved relations between the different agancies. This knowledge and information has been shared both by discussions and oral presentations at meetings and by joint field operations, like a comparison test of the two (at that time) only functioning softwares for Network RTK, GPSNet and Geo++.
- Avoid establishing too many reference stations: See below.
- Share parts of the development and drift costs: See below.
- Establish common GPS services: In this case it doesn´t have to be a homogenous service in the whole area. Instead it could be that through permanent reference stations on different sides of the border, a national service is created or improved (see below).
- Co-operate in the standardization work: This has been done both regarding how permanent reference stations should be established (see below) and regarding data formats and similar things.
- Increase the use of reference station data: This is something which isn´t measureable, but by finding new solutions of how to use it, the users should hopefully increase.

Present governmental GNSS services in the Nordic countries

Denmark:

- Only for post processing at moment.
- There will be a Network DGPS service when the Nordic Positioning Service sub project DPOS is finished (see below).

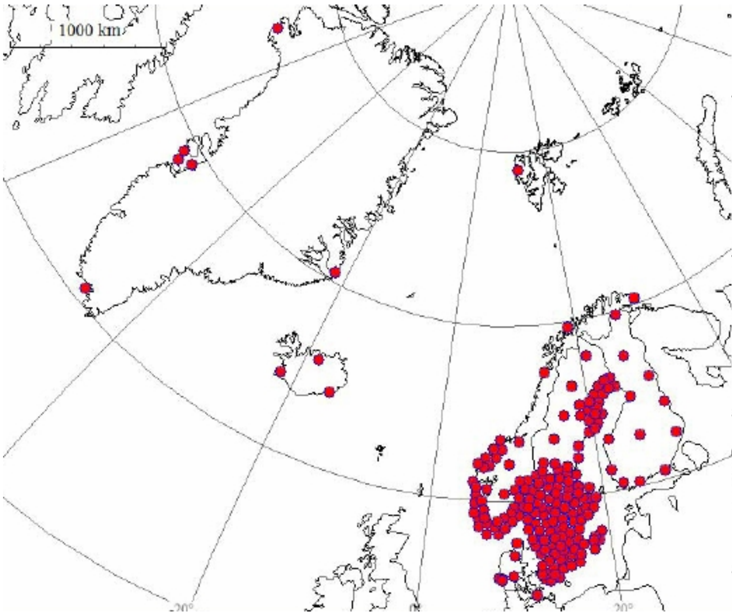

Fig.1. *The governmental permanent reference stations in the Nordic countries.*

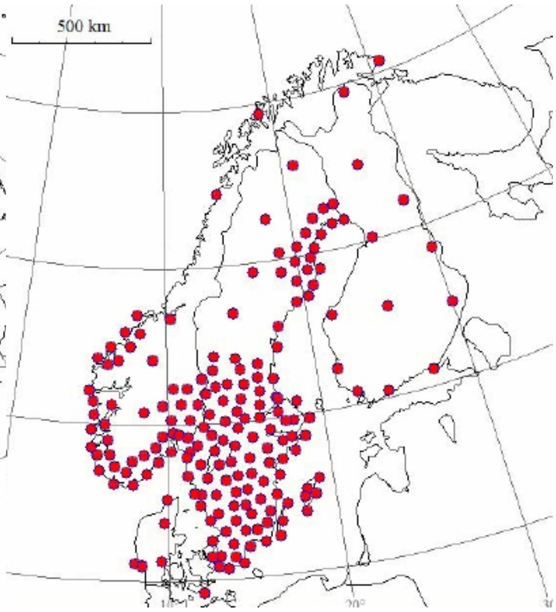

Fig.2. *The governmental permanent reference stations in the Nordic countries.*

Norway:

- CPOS. A Network RTK service, which consists of 39 stations at moment and covers parts of southern Norway. More CPOS stations are about to be established in the near future.
- DPOS. A Network DGPS service, which sort of covers the whole country. There will be better coverage along the borders when the Nordic Positioning Service sub project DPOS is finished (see below).
- MPOS. A DGPS service, which covers the whole country.
- For post processing.

Sweden:

- SWEPOS Nätverks-RTK tjänst. A Network RTK service, which consists of 120 stations at moment and covers the southern half of Sweden and some parts in the northeast. More stations are about to be established in next year.
- SWEPOS Nätverks-DGPS tjänst. A Network DGPS service, which sort of covers the whole country. There will be better coverage along the borders when the Nordic Positioning Service sub project DPOS is finished (see below).
- SWEPOS Efterberäkningstjänst. For post processing.

Finland:

- Only for post processing

Iceland:

- Only for post processing

The project structure

In February 2004 Nordic Positioning Service got a new project structure, which looks as the following:

- Nordic Postioning Network: In order to make the exchange of data possible. This sub project is almost finished now.
- A common Web-site: For finishing this, the sub project Nordic Positioning Network must be finished. Here the user will be able to download data for post processing from any Nordic station as long as he/she has a subscription in any of the countries.
- NorDPOS: For establishing Network DGPS services based on Nordic permanent reference stations.
- NordRTK: An information exchange sub project. Here information about Network RTK in general and the Network RTK software GPSNet is exchanged. Also the part about optimal distribution for Network RTK reference stations is handled here.
- Permanent GNSS standards: This sub project is finished, see Standardization below.

From the old project structure an old sub project is resting at moment, the one about A Nordic Computation Service. This sub project will be a further development of the Swedish SWEPOS Computation Service, consisting the whole area of Denmark, Norway and Sweden.

Previous and present work

Exchange of data

In 2002 the Directors General signed an agreement between KMS, LMV and SK about the exchanging of data for post processing from our permanent reference stations

for GPS/GNSS. The users in each country shall then be able to use data also from reference stations in the other countries, but only pay the subscription costs in the country they measure in. To make this vision come true, communication lines needed to be established between the three control centres, in København, Hønefoss and Gävle.
Here many problems have occured on the way to a finished solution:

- The computer environment. Norway and Denmark use Unix and Sweden uses NT.
- The data formats of different brands of GNSS receivers are not compatible. Here a standard should be required. Our solution was to develop a format for real time data transfer.

But finally in the autumn 2005 these problems could be solved and now this is working well.

GPS services
The first operative collaboration became a fact in the autumn of 2002 when a Nordic DGPS solution was shown at a Director Generals meeting in Denmark.
In the near future new or improved Network DGPS services will be established due to the Nordic co-operation. Three such services worth mentioning are:

- A new Network DGPS service in Denmark
- An improved Network DGPS service (improved DPOS) in northern Norway
- An improved Network DGPS service (improved SWEPOS Nätverks-DGPS) in the northwest of Sweden.

Co-operation along the borders
In Norway and Sweden areas for Network RTK has been established where enough users have been interested. Since a number of years ago there has been a Network RTK area in Norwegian Østfold, close to the Swedish border. When the Network RTK area in Sweden in the end of 2005 was about to include new stations in the areas along the Norwegian border the Network RTK co-operation became a fact. This resulted in that one of the Norwegian stations could be removed, which was cost saving. At moment four Norwegian stations are included in the Swedish Network RTK service, “SWEPOS Nätverks-RTK”, and seven Swedish stations are included in the Norwegian Network RTK service, “CPOS”.

Standardization
A sub project of Nordic Positioning Service got the mission to ensure that the permanent GNSS stations in the Nordic countries have the required quality with regard to their use, by performing a classification document. In the classification the stations are divided into four classes:

- A: Station which could be an IGS/EUREF station
- B: Station with Dorne Margolin antenna (or similar) on a building
- C: Station without Dorne Margolin antenna (or similar) on a building
- D: Station for navigational use only

This document shall now be used when new GNSS stations are established.

Other activities
The Nordic campaign about the EUREF-realizations in 2003 was an initiative from the Steering Committee. To make transformation connections between the different national systems is quite important if there will be common GPS services.

Summary and the future

A very brief summary what Nordic Positioning Service this far has resulted in is:

- An improved co-ordination of the network of governmental permanent reference stations for GNSS in Denmark, Norway and Sweden.
- A deeper exchange of knowledge and experiences in the field of establishment, operation and use of permanent reference stations.
- The establishment of a common base for future Nordic Positioning Services.

At the NKG General Assembly there was a resolution about this project, which said that the number of permanent stations for GNSS is increasing rapidly in the Nordic area and that there is a lot to gain by coordinating the establishment of permanent reference stations in the border areas between the Nordic countries and that there is a benefit to exchange data between the Nordic countries from permanent GNSS-stations and to exchange knowledge and experiences in the field of establishment, operation and use of permanent reference stations and that NKG recommends that the project Nordic Positioning Service continues the efforts to coordinate the Nordic networks of permanent reference stations and to establish Nordic Positioning Services.
A conclution of that is that the project will go on in the same way as before, which was the proposal by the Steering Committee.

Still the door is open for Finland or Iceland to take a more active role in this work, they are welcome any time to join the project or just take part in a meeting!

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Working Group for the Height Determination Activity report for the period 2002-2006

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Introduction

The Working Group for levelling is the one of the oldest working group in the NKG. It was established in the General Meeting in Oslo in 1978 and entitled as the Working Group on Levelling and Height Determination. The name was changed to the Working Group for Height Determination (WGH). Through its history the WGH has been working on problems of the ongoing precise levellings. The chairmen of the WGH have been

- Ole Bested Andersen 1978-1986,
- Jean-Marie Becker 1986-2002 and
- Mikko Takalo 2002-2006.

During the meeting of the Nordic Geodetic Commission (NKG) in Espoo October 2002 it was decided that the Working Group for Height Determination (WGH) should continue its activities over the period 2002-2006. The planned structure of the work included the following activities:

- Levelling data will be collected in the Nordic Countries
- Establish a Nordic levelling Database
- Create the common land uplift model
- Organize the height system co-ordination in Nordic
- Create a connection of Nordic Levelling Block to EVRF and ECGN
- Write the position paper of the state of art

When the WGH started the work in 2002 the status of the national levellings was as follows

- Denmark had already completed the National levelling and adopted the new height system DVR90 in 2001 (Klaus Schmidt 2000)
- The National levelling of Sweden was almost completed and an urgent task was to create a new Swedish height system. The height system RH70 was valid.
- The National levelling of Finland was also about ready and a new height system was planned to be ready at the end of 2006. The height system N60 was valid.
- The National levelling of Norway was still going on and it was estimated to be ready in 2007-2008. The height system NN 1954 was valid

The status of the national levellings in Baltic States was as follows

- Estonia had a plan to start the national levelling in the near future
- The national levelling of Latvia was in going on
- The national levelling of Lithuania would be ready after some years

As a conclusion of the status of the levellings in 2002, the leveling connection between the Nordic levelling Block and European network was weak and even the precise levelling over the Danish Straits along the new bridge was just completed.

Consequently, the main goals for the WGH in period 2002-2006 were

a) Establishment of national realizations of new height systems with good consistency between them and
b) the realization of the European Height System EVRS2000 and the Nordic Height Block should be connected stronger than earlier to the European network with a new connection over the Danish Straits and the Gulf of Finland.

These requirements will be realized by following actions:

- Adjustment of levelling networks around the Baltic Sea to create a common frame for the national height systems
- Create a common Nordic land uplift model and
- Define of the terms for national height systems.

Organisation

In the meeting of Akranes 2001 it was decided to establish two sub-working groups (SWG): Transfer and Computations group leaded by Mikael Lilje, and Land uplift group leaded by Jaakko Mäkinen (Figure 1). In 2003 the both sub-working groups were merged to one, Nordic Height Block group leaded by Jaakko Mäkinen. The reason was that mainly the same persons were participating to the work of both groups. To help the new

SWG, two small special groups or teams of 3-4 people came about, one for calculation and the other one for land uplift.

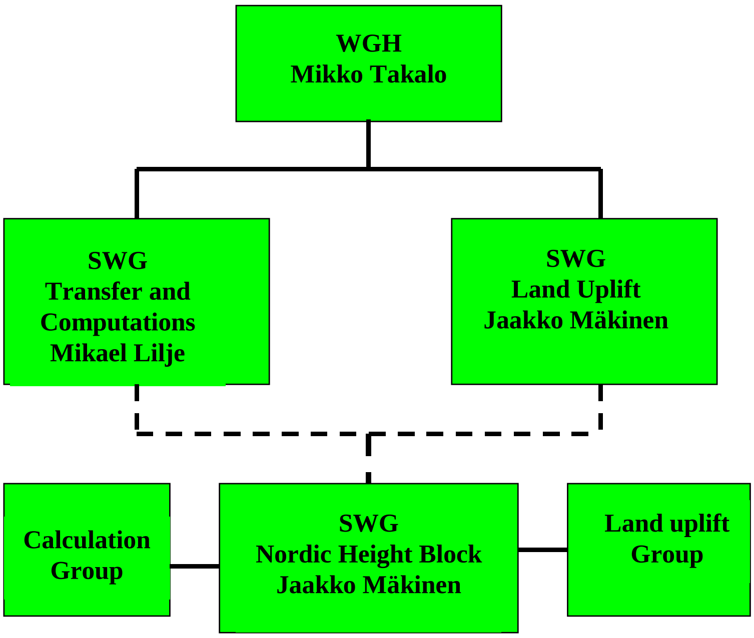

Fig. 1. *Organisation of the WGH.*

In order to activate the contacts with other working groups and the Presidium, the NKG nominated the following contact persons acting during the time period 2002-2006:

Klaus E. Schmidt <kes@kms.dk>
Casper Jepsen <cj@kms.dk>
Veikko Saaranen <Veikko.Saaranen@fgi.fi>
Olav Vestøl <vesola@statkart.no>
Per-Ola Erikson <per-ola.erikson@lm.se>
Per-Anders Olsson per-anders.olssom@lm.se

Risto Kuittinen was nominated to act as the contact person between working group for height determination and the Presidium. The WGH has reported five times to the Presidium in 2002-2006 and the chairman of the WGH participated once the meeting of the Presidium.

The working group has continued to have annual meetings, once a year and the sub working group has had its own meeting twice as follows:

Date	Place	Working group	Number of participants
20-21.10.2003	Hönefoss, Norway	SWG	13
31.3-1.4.2003	Copenhagen, Denmark	WGH/SWG	18
29-30.3.2004	Tallinn, Estonia	WGH/SWG	22
13-14.6.2005	Akranes, Iceland	WGH/SWG	14
18-19.4.2006	Gävle, Sweden	WGH/SWG	15
20.1.2005	Arlanda, Sweden	SWG	6

The meetings have been open for everybody interested in participating at the meetings and discussing current problems and activities of the height determination themes. The following geodesists have participated the meetings in 2002-2006:

Canada: Jan Kouba

Denmark: Casper Jespen
Karsten Ensager
Klaus Schmidt
S. Stampe Villadsen
Kirsten Johansen
Lola Bahl

Estonia: Andres Rüdja
Tarmo Kall
Harli Jürgenson

Kalev Kangur
Natalja Morozova
Adolf Ostonen
Ants Torim
Raivo Vallner
Priit Pihlak

Finland: Jaakko Mäkinen (Chairman of SWG)
Mikko Takalo (Chairman of WGH)
Veikko Saaranen
Pekka Lehmuskoski

Iceland: Markus Rennen
Þórarinn Sigurðsson
Gudmundur Valson

Latvia: Armand Celms
Jānis Kaminskis

Lithuania: Arunas Buga
Eimuntas Parseliunas

Norway: Olav Vestøl
Björn Engen

Sweden: Per-Anders Olsson
Per-Ola Eriksson
Runar Svensson
Mikael Lilje
Martin Lidberg
Jonas Ågren
Anders Olsson

Detailed minutes of each meeting have been sent to all members of the WGH and can be found on web page of the NKG.

Following papers have been presented in the meetings of the WGH and WGH/SWG

Copenhagen 2003

– Rene Forsberg: "Report of NKG2002-geoid"
- Klaus Schmidt: "Status of the computation of the Øresund loop closing error"
– Pekka Lehmuskoski: "Stability of Metsähovi test field"
- Mikko Takalo: "On application of the system calibration results"
- Klaus Schmidt: "Some theoretical aspects on different collocation approaches with reference to land uplift determination from repeated levelling"

Discussions of

- Height system in Sweden (Introduced by Mikael and Martin)
- Connection to NAP using UELN-95 through Denmark and through the Baltic countries (Introduced by Jaakko)
- Experiences of new height system in Denmark (Introduced by Stampe)
- Comparison and synthesis of land uplift rates (Introduced by Jaakko)

Tallinn 2004

- Per-Anders Olsson: "The implementation of RH 2000 in municipalities"
- Per-Ola Eriksson: "Maintenance of RH 2000"
- Klaus Schmidt: " The Closing of the Oresund loop"
- Mikko Takalo: "Long sightings using the digital level Zeiss Dini12"
  Harli Jurgenson: "The Difference between the N60 and BK77 Height Systems"

Akranes 2005

- Klaus Schmidt: "Results from closing the Øresund Loop"
- Per-Ola Eriksson and Mikko Takalo: "Problems of Zeiss DiNi12"
- Mikko Takalo: "The Third Levelling of Finland – 27 years project"

Gävle 2006

- Jaakko Mäkinen and Mikko Takalo: "New height system of Finland N2000"
- Jonas Ågren: "Land Uplift model (RH 2000 LU)"
- Olav Vestöl: "Status of Olavs land uplift model"
- Per-Ola Eriksson: "Problems of digital levels"
- Mikko Takalo : "Digital levelling system Zeiss DiNi12 - From bar code to height reading"

The major goal of the WGH during the period 2002-2006 has been to adopt the national height systems inside the Nordic Block, which are consistent both with each other and with the European height datum EVRF2000. That was realized by adjusting the network of the national levelling around the Baltic, which is called as Baltic Levelling Ring (BLR). Therefore the main topics of discussion in our meetings have been

In Copenhagen 2003

– Preliminary plan of the adjustment around the Baltic
– Contents and authors of the Position paper

In Hönefoss 2003

– Realisation for actions of the Position paper

In Tallinn 2004

– Adjustment around the Baltic and related topics: Land uplift, data from UELN

In Akranes 2005

– Results of the BLR and reporting

In Arlanda 2005

– The new height system of Sweden RH2000

In Gävle 2006

– Nordic Land Uplift model NKG2005LU

– National height systems

The WGH was organising the NKG Workshop “The Establishment of a New Vertical Reference for Iceland” June 15th-16th, 2005 in Reykjavik, Iceland.

RESULTS

In the following we report what the achievements during the four year period in co-operation with the Nordic Mapping authorities, Institutes and the Presidium.

- Nordic Database 2002
- Position paper 2003
- The agreement and the forms for data distribution from the Nordic Data Centre of levelling data 2004
- Adjustment of Baltic Levelling Ring (BLR) 2005-2006
- Recommendations for creating national height systems 2003
- Nordic land uplift model NKG2005LU 2005
- Height systems RH2000 2005 and N2000 2006
- Study of digital levelling system problems
- Seminar in Iceland: A workshop on the Establishment of a nationwide Icelandic Vertical Reference System 2005

Several articles have been written in 2002-2006 dealing with the BLR, land uplift, Nordic levelling Block, problems of levelling ets. Below only some few of them are listed.

Ågren J., Svensson R. (2005): Postglacial land uplift model for the computation of the third levelling of Sweden. Manuscript, submitted for publication

Jurgenson H., Kall T. (2004): The difference between N60 and BK77 height systems. Nordic Journal of Surveying and Real Estate Research Volume 1, Number 1, 2004

Mäkinen J., M. Lidberg, K. Schmidt, M. Takalo, M. Lilje, Engsager, P-O. Erksson, C. Jepsen, P-A. Olsson, V. Saaranen, R. Svensson, O. vestöl (2004): Future height systems in the Nordic countries, their relations to the EVRS2000 and to INSPIRE GIS standards. In: J.A. Torres and H. Hornik (eds), report on the Symposium of the IAG Sub commission for Europe (EUREF) held in Toledo, 4-7 June 2003. EUREF Publication No. 13.

Mäkinen J., M. Lilje, J. Ågren, K. Engsager , P-O. Erksson , C. Jepsen, P-A. Olsson, V. Saaranen, K. Schmidt , R. Svensson, M. Takalo, O. Vestöl (2006): Regional Adjustment of Precise Levellings around the Baltic. Submitted for publication

Ollikainen M., Rudja A., Jurgenson H., Mäkinen J. (2003): Height connection over the Gulf of Finland using oceanographic levelling, and GPS/geoid ties. Symposium of the IAG Commission X – Sub commission for Europe, EUREF 2003. Toledo, Spain, 4-7 June 2003

Saaranen V., Mäkinen J. (2002): Determination of the post-glacial rebound from the three precise levellings in Finland: Status in 2002. In: M. Poutanen, H. Suurmäki (eds), Proceedings of the 14th General Meeting of the Nordic Geodetic Commission, Espoo, Finland, October 1-5, 2002.

Vestöl O. (2005): Determination of the post-glacial land uplift from levelling, tide-gauges and continious GPS stations using least square collocation. Submitted for publication

Takalo M, Rouhiainen P. (2004): development of a system calibration comparator for digital levels in Finland. NJSR , 2(2)

Future works

The Height determination working group must continue its working in future, because

- The analysis of the adjustment of the BLR is not yet completed.
- The national levelling of Norway and the Baltic Countries are still going on.
- The technical development of the present height determination methods (precise levelling, trigonometric levelling), new methods and those applying the sea level and GPS/Geoid, belong to the scope of activities by the WGH.
- The study of the Nordic land uplift models will continue. New observations especially from the Baltic countries will be incorporated.
- The connection of the Nordic levelling Block to the European and the World height systems belongs also to the scope of activities by the WGH.
- The test field measurements, the error analyses and the study of the digital levelling technique will be the main issues by the WGH.
- In order to discover, study and apply new height determination methods, the co-operation with the other working groups of the NKG and also with the FIG, the IAG, etc. should be essential.

Thanks to the members of the WGH for the valuable and active co-operation in 2002-2006

Jan Kouba:

”Only the levellers are real geodesists”

Land Uplift Model and System Definition Used for the RH 2000 Adjustment of the Baltic Levelling Ring

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Abstract
The work to compute the latest precise levellings in Finland, Norway and Sweden has been made as a Nordic cooperation within the Working Group for Height Determination of the Nordic Geodetic Commission (NKG). It includes the compilation of the Baltic Levelling Ring (BLR), consisting of precise levellings from all the Nordic and Baltic countries as well as Poland, Germany and the Netherlands. The main purpose of this paper is to describe the postglacial land uplift model and system definition that were utilised for the Swedish adjustment of the BLR, which constitutes the Swedish height system RH 2000.

It was decided that the new system should be a realisation of the European Vertical Reference System (EVRS) using the Normaal Amsterdams Peil (NAP) as zero level. The final land uplift model is a combination of the geophysical model of Lambeck, Smither and Ekman and the mathematical (empirical) model of Vestøl. It has later been adopted as a Nordic model with the name NKG2005LU. We describe the path leading to this model and analyse the consequences of the chosen definition and uplift model by comparing the resulting heights to Mean Sea Level in the Nordic and Baltic Seas and to a few other height systems.

1. Introduction
In 2005 Sweden introduced the new National height system RH 2000. It is the final result of the third precise levelling of Sweden. The computation was made in Nordic co-operation within the Working Group for Height Determination of the Nordic Geodetic Commission (NKG) and with EUREF (IAG Reference Frame Sub Commission for Europe). The adjustment includes observations from the whole Baltic Levelling Ring consisting of the precise levellings from all the countries around the Baltic Sea as well as Northern Germany and the Netherlands.

To reduce the observations to a common reference epoch, the postglacial land uplift model NKG2005LU was constructed. It is computed as a combination of the mathematical (empirical) model of Vestøl (2005) and the geophysical model of Lambeck et al. (1998); see also Vestøl (2006) for a full documentation of a later, modified version of the model. To obtain heights agreeing as closely as possible with the other European countries, the system is defined to be a realisation of the European Vertical Reference System (EVRS); cf. Ihde and Augath (2001) and the EUREF homepage (2005). It should be noticed, however, that it has so far not been defined on the European level how the phenomena of postglacial rebound should be treated.

It is the main purpose of this paper to introduce the third precise levelling of Sweden, present the Baltic Levelling Ring, describe the RH 2000 definition and summarise the path leading to the land uplift model NKG2005LU. It is also the aim to analyse the consequences of the definition and the land uplift model by studying the height of the Mean Sea Level (MSL) along the Swedish coasts and by comparing RH 2000 to the old Swedish height system RH 70 and to the European Vertical Reference Frame (EVRF 2000).

2. The third precise levelling of Sweden
The fieldwork of the third precise levelling of Sweden started in 1979 and the last line in the network was observed in 2001. See Becker (1984) and Becker et al. (1998) for more details concerning the third precise levelling. The main reason for starting yet another levelling in 1979 was that the previous levellings were not sufficiently accurate at the same time as the coverage of the country was too poor; see Fig.1. The aim of new third precise levelling is thus to create a homogeneous network covering the whole country, dense enough to allow *all* local users to connect their measurements to easy accessible benchmarks. Another aim is to achieve a better estimation of the land uplift by comparing the new levelling with the first and second counterparts (Eriksson et al. 2002). The network of the third precise levelling is dense and homogeneous at the same time as all levelling was carried out using the same technique and equipment. Considering the length of the project, the latter fact is quite remarkable. The benchmarks should thus be accessible to the users and the quality of the resulting RH 2000 heights should be high and homogeneous.

The network consists of approximately 50 000 km double run levelling and the number of benchmarks is

50 800. The distance between them is about 1 km. The network covers the whole country in closed loops, with a circumference of approximately 120 km, except for the mountain areas to the North-West where the roads are few. This makes it impossible to achieve the same density there; see Fig. 1. However, since the population is also very sparse in these areas, this is not too critical. The lines are connected to the levelling lines of our neighbouring countries, which results in closed loops along the borders. This also makes it possible to extend the network to the whole Baltic Levelling Ring; cf. Sect. 3. The network was planned in co-operation with the local users in order to increase the utility of the points for the connection of local measurements.

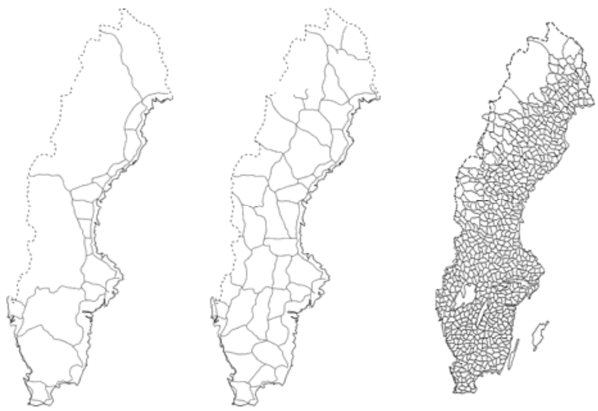

Fig. 1. *The network of the first, second and third precise levellings of Sweden (in the order mentioned from left to right).*

The observations were carried out by means of the motorised levelling technique using one instrument car and two rod cars (e.g. Becker et al. 1998; 2001). The instrument is a Zeiss Jena NI002 with a 360 degree rotating eyepiece and a reversible pendulum giving a quasi-absolute horizon. The rods are 3.5 m invar staffs with double scales. A separate 3.0 m invar rod is used for the connection to the benchmarks. The average sight length is approximately 35 meters (50 meters allowed). To make it possible to determine the land uplift, accessible points from the former precise levellings were connected to the network. The rejection limit was 2√L mm (L in km) during the whole project, which corresponds to a 2-sigma limit. If the measurements of a section differed more than this limit, then the section was relevelled. About 7 % of all sections have been remeasured for this reason. The whole production line, from the observations to the archive, is digital.

3. The Baltic Levelling Ring

As mentioned in the introduction, a large part of the processing of the precise levellings of Sweden, Finland and Norway has been made as a Nordic co-operation under the auspices of NKG. Denmark also contributed actively to the task, even though the Danish height system DVR 90 had already been finalised at the time (Schmidt 2000). To be able to connect to the Normaal Amsterdams Peil (NAP), which is the traditional zero level for the United European Levelling Network (UELN), and to be able to determine the relations to our neighbouring countries, it was decided to extend the Nordic network with the precise levellings from the Baltic States, Poland, Northern Germany and the Netherlands. The non-Nordic data was provided by EUREF from the UELN-database.

The whole network, which has been named the Baltic Levelling Ring, is illustrated in Fig. 2. Unfortunately, it has not been possible to close the ring with levelling observations around the Gulf of Finland. However, by means of other information (sea surface topography or GPS in combination with a geoid model), closing errors may still be computed. This amounts to a valuable check of the adjustment. It should be noticed, though, that only levelling observations are included in the final adjustment. As can be seen in Fig. 2, the Baltic Levelling Ring extends over a quite large area. To be able to reduce all observations for the postglacial land uplift, the applied model should naturally cover the same area. This should be kept in mind in what follows.

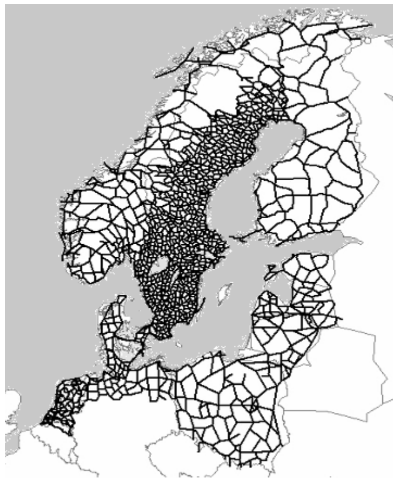

Fig. 2. *The Baltic Levelling Ring.*

4. System definition of RH 2000

As mentioned in the last section, much of the work to process the Baltic Levelling Ring was made as a Nordic co-operation within the NKG. This also includes the choice of system definition (datum) and the construction of a land uplift model; see for instance Mäkinen et al. (2004). However, the work on system definition and land uplift model had to be finished by Sweden in January/February 2005 (Ågren and Svensson 2006). At that time, most aspects of the definition had already been discussed on the Nordic level, for instance the common reference epoch for the postglacial land uplift.

Now, it was first decided that RH 2000 should be defined as the Swedish realisation of the European Vertical Reference System (EVRS). The main reason for this was to arrive at a system that agrees as well as possible with other

European systems. From this decision it follows that (EUREF homepage 2005; Ihde and Augath 2001):

- The **zero level** is given by the geopotential number from the latest official UELN-solution (EVRF 2000) for the Normaal Amsterdam Peil (NAP). It is true that NAP is not strictly a part of the definition of the EVRS, but at the time it was the only available alternative to realise EVRS (as for EVRF 2000).
- **Normal heights** are utilised.
- The **zero system** is utilised for the permanent tide.

One problem with the present EVRS definition is that no advice is given of how the postglacial land uplift should be treated. This means that these matters had to be taken care of at the Nordic level. Since the postglacial rebound is a very significant phenomena (see the next section), the system definition for RH 2000 should include a specification of how the land uplift is handled. The RH 2000 definition therefore includes the following items:

- The **reference epoch** for the reduction of postglacial rebound is 2000.0. This was decided at the Nordic level within the NKG.
- The **postglacial land uplift model** is NKG2005LU. The construction of this model is described in Sect. 6.

It should be pointed out that the RH 2000 definition is applied for the adjustment of the whole Baltic Levelling Ring, even though RH 2000 is strictly only a Swedish system.

5. Observations of the Postglacial rebound of Fennoscandia

The Nordic area (Fennoscandia) still experiences postglacial rebound after the melting of the ice covering Northern Europe some 10 000 years ago. The maximum uplift is approximately 1 cm per year; see for instance Fig. 3 below. This means that in projects with geodetic measurements conducted over long time periods in high accuracy applications, the phenomena must be taken into account somehow. To correct all measurements to a suitable reference epoch (see the last section), a model describing the uplift is needed.

The land uplift can be determined using different types of observations. For the construction of a land uplift model for the computation of the Baltic Levelling Ring, the most important types are,

- *Tide gauge (mareograph)* observations of the Mean Sea Level (MSL), from which the *apparent uplift* is determined by linear regression. In the present project, the uplift values derived by Ekman (1996) in 58 mareographs are used. Ekman estimates the standard error of these velocities to 0.2 mm/year.
- The *absolute land uplift* estimated from times series at *permanent GPS* stations. It should be noted that this type of uplift refers to a global reference frame, which is fixed with respect to the center of mass of the Earth. For the present project, the velocities from the BIFROST project as computed by Lidberg (2004) has been the main source of GPS derived land uplift. The standard error are estimated by Lidberg (ibid.) to 0.2–0.6 mm/year, but he concludes that these values are likely too low.
- The third type of observation is repeated *precise levelling* in Finland and Sweden (three levellings in each country). In Norway, the levelling has (more or less continuously) been going on during the last hundred years, but has not been systematically repeated at the same lines. Since the lines from different epochs are nevertheless connected in a network, the uplift can be determined; see Vestøl (2006) and Ågren and Svensson (2006). The uplift from precise levelling is *with respect to the geoid*. It is often referred to as the *levelled uplift*.

Above the main type of observations of the land uplift phenomena has been summarised. It should be stressed that they yield different types of land uplift. The apparent uplift $\dot{H}_a$ is related to the uplift with respect to the geoid $\dot{H}$ (levelled uplift) as

$$\dot{H} = \dot{H}_a + \dot{H}_e \qquad (1)$$

where $\dot{H}_e$ is the mean sea level rise. In this paper, the approximation is used that the absolute uplift $\dot{h}$ is linearly related to $\dot{H}$ (Ekman and Mäkinen 1996a); see e.g. Sjöberg (1989) for more strict formulas. Furthermore, the formulation used in practice by Vestøl (2005) is preferred:

$$\dot{h} = \dot{H} + s \cdot \dot{H} \qquad (2)$$

where s is a scale factor. Notice that the scale factor here refers to the levelled height and not, as is usually the case in this context, to the absolute uplift. Vestøl (2005) estimates $\dot{H}_e$ to 1.32 mm and s to 6% using the above mentioned observations. This relationship is assumed in this paper.

6. Derivation of a land uplift model

As mentioned above, the work to construct a land uplift model has been conducted in Nordic collaboration. The first part of this work was to evaluate the existing land uplift models to find out to what extent they are suitable for the task. After that, it was decided to combine them to reach the best possible result. Below, the three main evaluated models are first described. After that, the combination procedure leading to the final uplift model is summarised. It should be pointed out that more models than the ones presented here have been considered, but only the three main candidates are treated in this paper.

6.1 The model of Ekman (1996)

The first model is the one by Ekman (1996), which has been constructed using repeated levelling, the apparent uplift estimated from long time series at 58 tide gauges and some lake level observations. The main problems with this model for the present task are that it only uses the first and second precise levellings in Sweden, that it is based on no information in much of the interior parts of Sweden as well as Norway and that it does not cover the whole area of the Baltic Levelling Ring. In addition, no uplift values from GPS were available to Ekman (ibid.). Due to these reasons, it was concluded that this model is not suitable for the task.

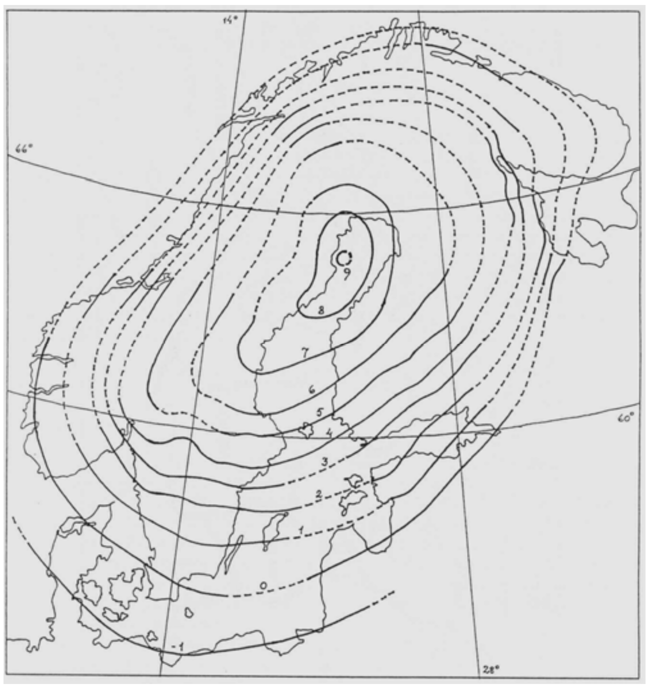

Fig. 3. *Apparent uplift from the model of Ekman (1996). Unit: mm/year.*

6.2 The geophysical model of Lambeck, Smither and Ekman

Another alternative is to use a geophysical model, which consists of a physical model of the lithosphere, the mantle and the ice sheet. One advantage of this kind of model is that it may provide a geophysically meaningful interpolation and extrapolation of the uplift phenomena. For instance, from the fact that the lithosphere is comparatively rigid, it follows that the land uplift model should be smooth. The lithosphere can sustain loads of smaller dimension.

Now, the geophysical model of Lambeck et al. (1998) was singled out as the best geophysical model available. This model has been tuned to the apparent uplift in the tide gauges referred to in the last subsection (Ekman 1996), some lake level observations and ancient shore lines. The model was only available as a digital image from the publication, meaning that it had to be digitised for the purpose. The digitised version (NKG) is here referred to as Lambeck's model is presented in Fig. 4.

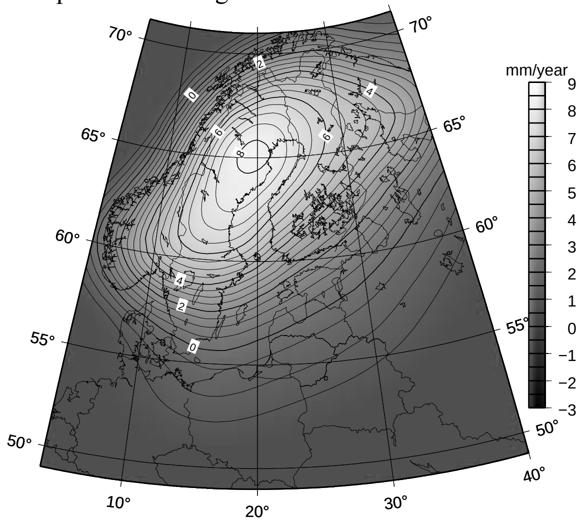

Fig. 4. *Apparent uplift according to the model of* Lambeck *et al. (1998). Contour interval: 0.5 mm/year.*

The evaluation of Lambeck's model was made by studying the residuals of tide gauge and permanent GPS observations, the latter being converted to apparent land uplift by the relationship at the end of Sect. 5. The result is illustrated in Fig. 5.

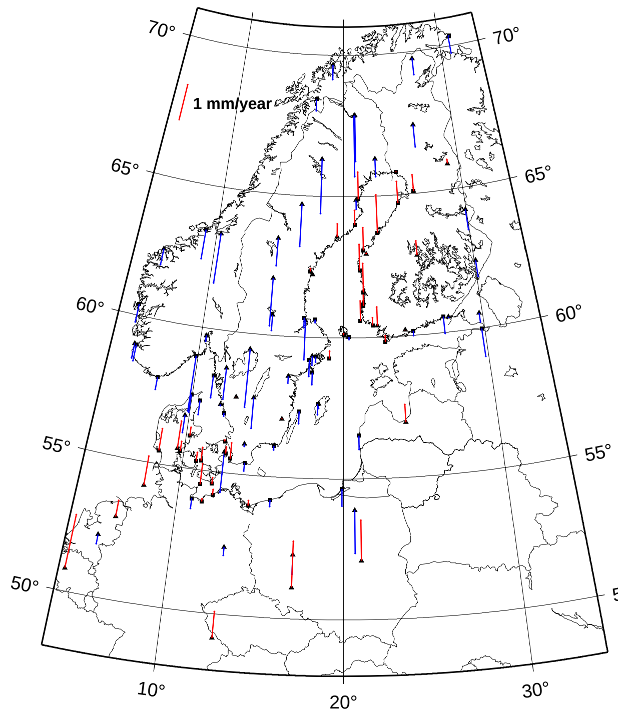

Fig. 5. *Tide gauge and GPS residuals for the Lambeck model. The tide gauges are denoted by squares and the GPS stations by triangles. The scale is given by the 1 mm/year arrow to the North West.*

It can clearly be seen that the model is very biased for the interior parts of Sweden. The errors are systematically as large as 1-1.5 mm/year. Mainly due to this reason, it was decided that the geophysical model of Lambeck et al. (1998) could not be used. Since it was out of the question to compute a new geophysical model, it was then decided to go for a mathematical (or empirical) model or to modify Lambeck's model for those areas in which better information is available.

6.3 Vestøl's Mathematical Model

A mathematical (empirical) land uplift model consists of a mathematically defined surface that has been constructed to fit the available land uplift observations in some suitable way. In 2005, one such model had been developed by Olav Vestøl from the Norwegian Mapping Authority. Since then, Vestøl has continued to improve his model (Vestøl 2006), but here only the version available in January 2005 (at the RH 2000 deadline) is treated. It is presented in Vestøl (2005); see Ågren and Svensson (2006) for additional details. The land uplift observations are those summarised in Sect. 5. By means of least squares collocation with unknown parameters using a polynomial trend surface of degree 5, the land uplift is estimated in the observation points. From these point uplift values, the land uplift is finally estimated in a grid by a simple gridding algorithm (mean of four observations, one in each search quadrant if closer than 120 km). The model is illustrated in Figs. 6 and 7.

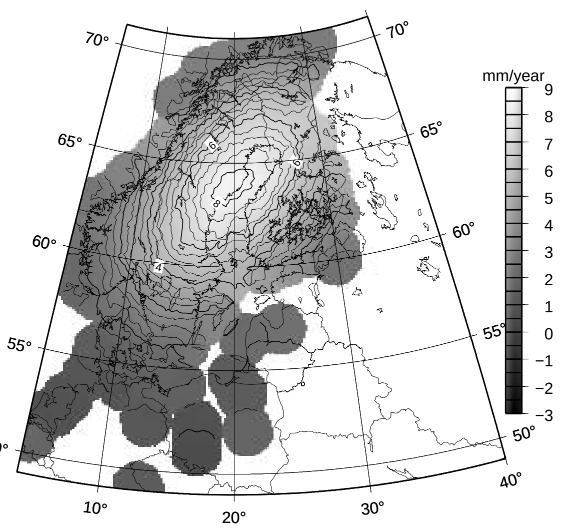

Fig. 6. *Apparent uplift according to the model of Vestøl (2005). Contour interval: 0.5 mm/year.*

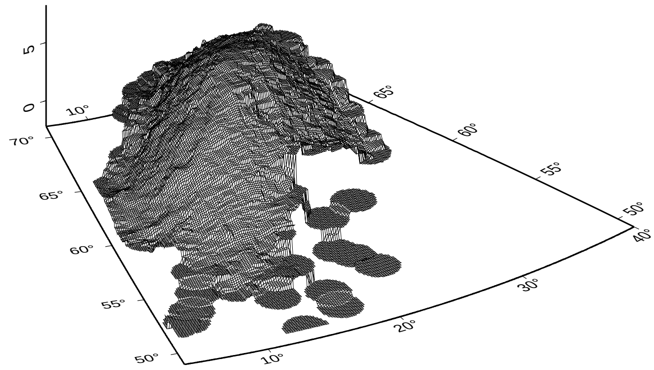

Fig. 7. Wireframe plot of the model of Vestøl (2005)

The model agrees well with the observations but is not defined for the whole BLR, which is a drawback. Few observations outside the Nordic countries are included and the simple gridding algorithm leads to strange "staircase cylinders" at the outskirts of the model. This behaviour can be clearly seen in Fig. 7, especially to the South. Furthermore, the model looks a little too rough with zigzag contour lines). Consequently, some smoothing might be motivated. One problem with a mathematical land uplift model is that it is not evident how the algorithm should be "tuned".

6.4 Combination of Vestøl's and Lambeck's Models (NKG2005LU)

One clear advantage of Lambeck's model is that it covers the whole Baltic Levelling Ring area in a reasonably realistic way. Vestøl's model does not. On the other hand, Vestøl's model fits much better with the observations over the Nordic countries compared to Lambeck's model. Therefore, a combination of the two models seems like the best possible choice to cover the whole area, all the way down to NAP.

Many different ways to optimise the combination have been explored, which will not be described in this paper. Interested readers can study Ågren and Svensson (2006). The final model, which was originally called RH 2000 LU (Ågren and Svensson 2006), is basically a smoothed version of the model of Vestøl (2005) in the central (Nordic) parts of the area. Outside this, a smooth transition to Lambeck's model is accomplished. The RH 2000 LU model has later received a more official status within the NKG and has been named NKG2005LU. The model, which is illustrated in Fig. 8, was applied in the RH 2000 adjustment of the Baltic Levelling Ring. The tide gauge and GPS residuals are illustrated in Fig. 9.

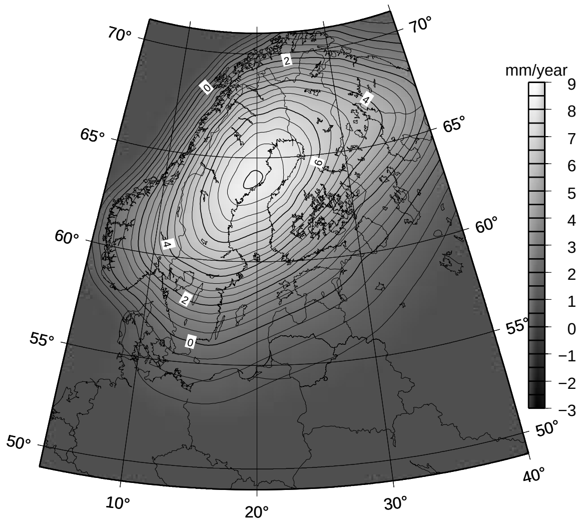

Fig. 8. *Apparent land uplift according to the NKG2005LU model. Contour interval: 0.5 mm/year.*

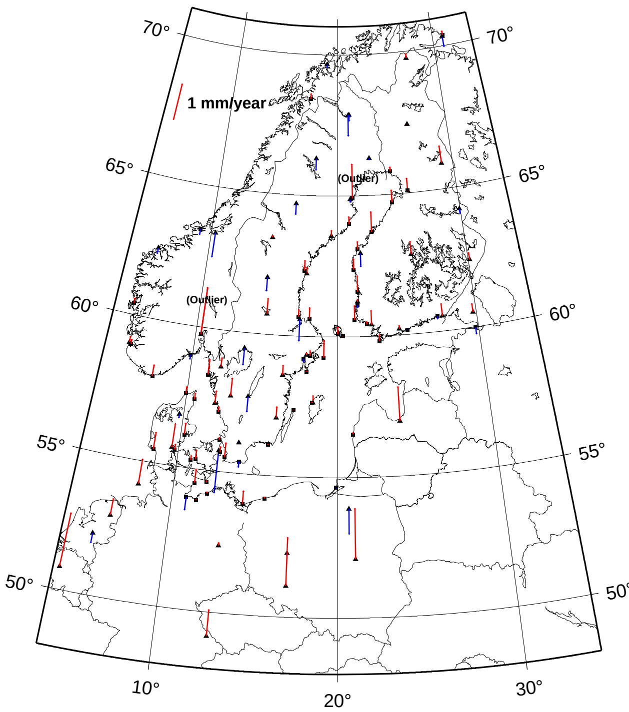

Fig. 9. *Tide gauge and GPS residuals for the NKG2005LU model. The tide gauges are denoted by squares and the GPS stations by triangles. The scale is given by the 1 mm/year arrow to the North West.*

If Figs. 5 and 9 are compared, it can be seen that NKG2005LU fits considerably better with the observations than the model of Lambeck et a. (1998). At the outskirts of the area, the two models are similar, though, which is only what could be expected.

7. Adjustment of RH 2000

All levelling data from the whole Baltic Levelling Ring was included in the final adjustment. It should be stressed that *only levelling observations* were utilised. In the first step, one least squares adjustment was made of the geopotential differences between a total of 7 400 nodal points, of which 5132 are Swedish. The national data sets in the Baltic Levelling Ring were given the weights determined by Karsten Engsager on behalf of NKG. The Swedish aposteriori standard error of unit weight is approximately 1 mm/√km. The estimated standard errors with respect to the NAP are illustrated in Fig. 10. As can be seen, they are approximately 2 cm in Sweden. In case the standard errors are transformed so that they refer to a fixed station in Sweden, for instance Gävle, they become smaller than 1 cm for the whole country, increasing approximately as the square root of the distance. The relative standard errors inside Sweden are thus below 1 cm, which is important in practice.

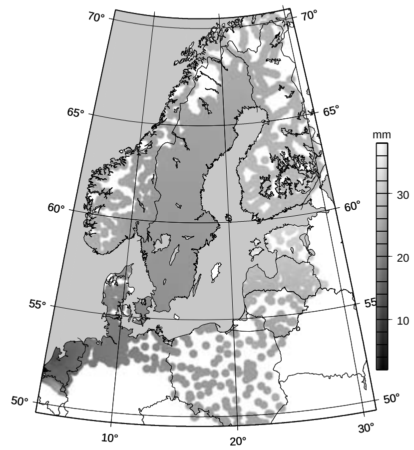

Fig. 10. *Estimated standard errors relative to NAP. Unit: m.*

The result from the first adjustment, which is geopotential numbers at the nodal benchmarks, was then used as known values in the adjustment of all other benchmarks. In total, about 50 000 points have been determined in RH 2000. In the final step, the geopotential numbers were converted to normal heights.

The construction of the land uplift model NKG2005LU was described in Sect. 6. The model is similar to the model by Lambeck et al. (1998) at the outskirts of the area, but is an improvement of the latter for the central, Nordic parts. An important question at this point is how much this means in practice, as judged by the difference for the adjusted heights. The height differences between applying the two models are illustrated in Fig. 11. As can be seen, the deviations are largest in Norway, but they are definitely significant also in Sweden. Here the adjusted heights differ approximately 1-2 cm. Another conclusion is that the difference changes the geometry of the heights. It is concluded that the choice of land uplift model yields significantly different heights. Since the NKG2005LU model agrees best with the observations, it is believed that the choice of this model for the RH 2000 adjustment is warranted.

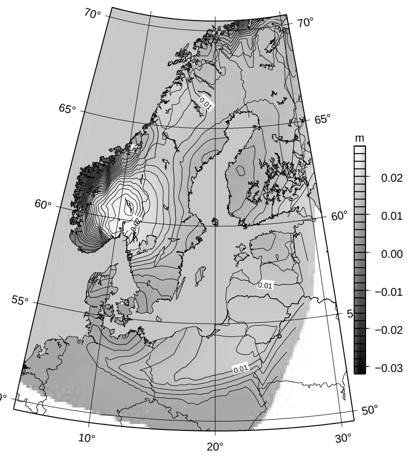

Fig. 11. *Adjusted height differences between using the land uplift model of Lambeck et al. (1998) and the NKG2005LU model. Contour interval: 0.01 m.*

8. Comparison of RH 2000 with MSL and two other height systems

Above the choice of system definition and land uplift model for RH 2000 has been described. It is important to notice that these choices have not been preformed blindly. Naturally we have studied the resulting RH 2000 heights and compared them both with the Mean Sea Level (MSL) along the Swedish coast and with other height systems. We would, for instance, not have accepted NAP as zero level in case the resulting MSL was completely inappropriate in the Baltic Sea. It is the main purpose of this section to study the MSL in RH 2000 at the Swedish coasts. Another aim is to compare RH 2000 with the older Swedish height system RH 70 and with the European Vertical Reference Frame 2000 (EVRF 2000).

The MSL in RH 2000 at the epoch 2000.0 for 4 Swedish mareographs is illustrated in Fig. 12. The computation was made as a linear regression using 90-120 years of observations lasting until 2001. The data were obtained from the Swedish Meteorological and Hydrological Institute (SMHI). No corrections were applied to the sea level observations.

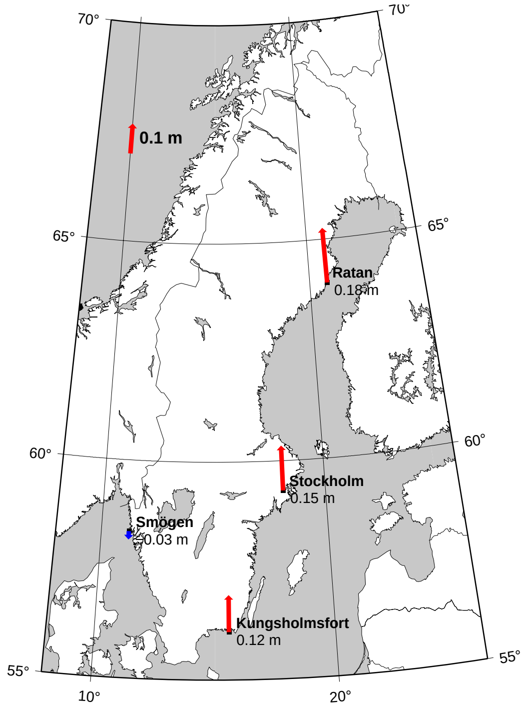

Fig. 12. *Mean Sea Level (MSL) in RH 2000 at 4 tide gauges. Epoch: 2000.0.*

By studying Fig. 12, it can be seen that the MSL is reasonably close to zero in the Western parts of Sweden and that the magnitude increases the further North one moves in the Baltic Sea. The main deviation is due to the sea surface topography and the fact that a zero permanent tide system is used for RH 2000; see Ekman and Mäkinen (1996b). Only in a mean system, the MSL adjusts to the sea surface topography. Due to the mentioned effects, it is not possible to choose a zero level for RH 2000 so that the MSL becomes zero everywhere. Seen in this light, the obtained result seems pretty good. The MSL is almost zero at the West coast and increases the further one moves in the Baltic Sea, which is appropriate considering the sea surface topography (Ekman and Mäkinen 1996b). It should also be noticed that what is discussed here is the MSL at the reference epoch 2000.0. As times moves on, the sea level will reduce due to the land uplift. This means that the MSL in RH 2000 will become smaller and become even closer to zero. It is concluded that the choice of NAP as zero level yields a system with heights agreeing reasonably well with the MSL at the Swedish coasts. There is no reason to define RH 2000 using the mareographs along the Swedish coasts.

Let us turn now to the comparison of RH 2000 with the old RH 70 (epoch 1970.0 using a non-tidal permanent tide system). The difference in heights varies between 7 and 32 cm, which can mainly be explained by the different land uplift epochs and by the different permanent tide systems; see Ågren and Svensson (2006) for more details and a longer discussion. If all the known effects are corrected, the differences in Fig. 13 are obtained.

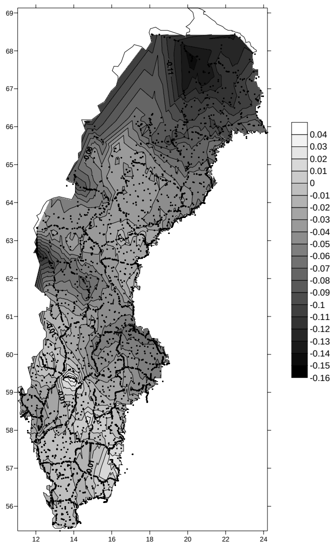

Fig. 13. *Difference between RH 2000 computed with NKG2005LU and RH 70 with corrections applied for the land uplift epochs and permanent tide systems. Unit: m. Contour interval: 0.01 m.*

It is believed that the differences in Fig. 13 are more or less what can be expected, considering the quality and denseness of RH 70; see Ågren and Svensson (2006). Since RH 2000 can be expected to be considerably better than RH 70, it is believed that Fig. 13 mainly illustrates the errors of RH 70.

Next, RH 2000 is compared with the latest realisation of EVRS (available at the beginning of 2005); see Ihde and Augath (2001). The differences between RH 2000 and EVRF 2000 at a number of nodal benchmarks are illustrated in Fig. 14.

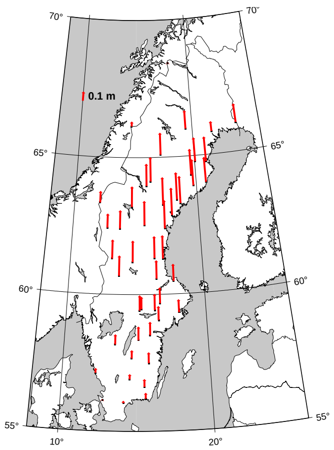

Fig. 14. *Difference between RH 2000 and EVRF 2000 at a number of Swedish nodal benchmarks. The scale is given by the 0.1 m arrow to the North West.*

It should be noted that the differences between RH 2000 and EVRF 2000 are very large. This mainly depends on that the land uplift epoch 1960.0 is used for Nordic countries in EVRF 2000. It is important to keep this in mind. The rather similar names might otherwise give the impression that the heights of these systems should be similar.

9. Final words

It has been the main purpose of this paper to describe how the new Swedish height system RH 2000 is defined as a realisation of EVRS, to present the construction of the land uplift model NKG2005LU and to study the final RH 2000 heights. Besides this, the third precise levelling of Sweden, the Baltic Levelling Ring and the RH 2000 adjustment has been described in some detail.

The work to implement RH 2000 among other authorities in Sweden, such as municipalities, is in progress. In general, these authorities have their own height systems and most of them even have more than one system to work with. This situation complicates the exchange of height information and the use of GPS for height determination. Lantmäteriet is here acting as an advice board. Currently, approximately 45 of the 290 Swedish municipalities have, in co-operation with Lantmäteriet, started the process to recalculate and analyse their local networks, with the aim of replacing the local height systems with RH 2000. So far, four municipalities have finalised the replacement for all activities, but the work has yet only started.

Acknowledgements

We thank all members of the NKG Working Group for Height Determination, especially Karsten Engsager, Jaakko Mäkinen, Veikko Saaranen and Olav Vestøl. We also thank Johannes Ihde and Martina Sacher, EUREF (IAG Subcommission for Europe) and the responsible agencies for providing the levelling data of the non-Nordic countries to the project.

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The future of height systems and vertical datums

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We are at the threshold of technology jump that will change the determination of geopotential values and geopotential differences (i.e., of heights) on global, continental and even on a national scale. With the precise geopotential models from the current (CHAMP, GRACE) and future (GOCE) gravity satellite missions, height differences can be determined from a combination of gravity data and 3-D positions with accuracy at least comparable to that of precise levelling already over medium distances. Averaging a geopotential model over a levelling network, even a medium-sized country will be able to access a world height datum defined by a geopotential value, without e.g. ties to tide gauges or even across borders. Thus national or regional tide gauge datums could soon be replaced by vertical reference system(s) and reference frame(s) based on a global system and its realizations, in the same way as historical horizontal datums are everywhere being replaced by 3-D coordinate systems derived from the ITRS and its realizations. And as with 3-D positions, the contemporary measurement accuracy means that heights cannot be considered time-invariable any more.

Quality of Geodetic GPS

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1 Introduction

In Finland GPS has been used for surveying since the late 1980's. Surveyors have utilised different modes of the GPS as soon as they have become available. In the beginning of GPS era static measurements rapidly took over traditional surveying methods. Nevertheless exact information about accuracy, reliability and required session durations were missing. Surveyors were dependent on the information from various sources and their own experiences. Even today Finnish surveying society is lacking consistent and research-based knowledge of optimum way of using GPS.

Since the mid-90's real-time GPS modes have been developed and adopted rapidly for conventional mapping etc. Easiness and productivity of real-time measurements have widened the spectrum of applications and users. However, real-time methods have brought a new feature, uncontrollable reliability, along with instant results. Traceability chain has broken and statistical estimates are not available for the results. New real-time applications have also blurred the traditional way of measuring coordinates hierarchically. These issues have lead to urgent need for extensive studies on quality of such techniques.

Finnish Geodetic Institute has an ongoing project that studies the quality of geodetic GPS. The goal of the project is to investigate both real-time and post-processing geodetic GPS in practice. Real-time applications, namely real-time kinematic (RTK) and Virtual Reference Station (VRS™) concept, were studied in 2003-2005 and static GPS in 2005-2006.

2 Reference data

2.1 Coordinate frames

Advisory Committee on Information Management in Public Administration, JUHTA, has given recommendations for the public administration (JHS recommendations) concerning the coordinate systems and frames in Finland. JHS recommendation 153 was given in 2002. It deals with ETRS89 coordinates and defines the national realization of ETRS89 in Finland. This realization is called EUREF-FIN (JHS 153, 2002). In the recommendation JHS 154 map projections to be used with EUREF-FIN are described (JHS 154, 2003). There is also a new guideline for planning a surveying in Finland (MML, 2003). This guideline recognizes the ETRS89 as an official coordinate system in Finland.

Finnish Geodetic Institute maintains permanent GPS network of 13 stations, FinnRef. FinnRef creates a link to the international coordinate frames like ITRF and serves as the basis of EUREF-FIN. FinnRef and 100 benchmarks tied to it with 48-hour observation time define the ITRF-based EUREF-FIN (Ollikainen et al., 2000). This network was further hierarchically densified with 350 points by the FGI in 1998-1999 (Ollikainen et al., 2001).

The processing of 100-point EUREF-FIN frame was done with Bernese 4.0 software with precise ephemerides. The rms accuracy of final adjustment was ±2 mm for the North and East components and ±6 mm for the heights. (Ollikainen et al., 2000, 2001). The densification of EUREF-FIN was carried out with 6-hour long GPS sessions and the processing was done with Pinnacle software. The final adjustment was done with Global-X software. The rms of the final adjustment was ±4 mm for the North and East components and ±6 mm for the heights. (Ollikainen et al., 2001).

2.2 Test fields

2.2.1 RTK test field

For the RTK test an adequate test field that covers distances up to 30 km was needed. Such test field did not exist and therefore FGI created a test field of 10 points in vicinity of municipality of Kirkkonummi (Figure 1). RTK test field covers distances between 0.4 and 25 km from the base station. The points are appropriate for GPS observations and they are mounted on bedrock or other stable foundations. The reference coordinates of test field were determined with minimum of three hours of static observations in order to ensure the precision of the network. Computation of the network was performed with Trimble Total Control GPS processing software and it was fixed to the EUREF-FIN coordinates of the Metsähovi station. Standard error of the adjustment is ±1 mm for the North and East components and ±2.5 mm for the height. This indicates that the test field is precise due to a common adjustment. (Häkli and Koivula, 2005).

Fig. 1. *RTK test field of 10 points.*

2.2.2 VRS test field

VRS measurements were carried out in two different and detached VRS networks (Figure 2). Half of the measurements were done in GPSNet.fi network and other half in the network of Tampere region. The same requirements for the reference points as in RTK test field were applied. However, the test points belong to different networks (see Figure 4) and are therefore not as homogeneous as the points in the RTK test field. The VRS test points are evenly distributed with respect to baseline length in order to study distance-dependency. (Häkli, 2004) (Häkli and Koivula, 2004).

Tampere region

The VRS network of Tampere region consists of four permanent GPS stations (open circles in Figure 2). Their inter-station distance varies from 20 km to 61 km, while average distance is 42 km. The reference stations (I order network of Tampere) are tied directly to five FinnRef stations with 24-hour sessions. The data was processed with Pinnacle and adjusted with Global-X softwares. Rms of the reference station coordinates is ±5 mm. The test points are II and III order benchmarks of the Tampere GPS network (see Figure 4). II order network consists of 13 points and they are fixed to the VRS network with 3-4 hours static observations. The standard error of the II order network is ±6 mm. III order network consists of 155 triangulation and traverse points in municipality of Tampere. The session durations varied from 45 minutes to 2 hours (Häkli, 2001). The standard error is ±6 mm. 12 test points from the II and III order networks and six points from the EUREF-FIN densification network were selected to the test field within the VRS network of Tampere region (small circles in Figure 2).

GPSNet.fi

VRS network of Geotrim Ltd., GPSNet.fi, consisted of 16 permanent GPS stations at the time of the measurements (large triangles in Figure 2). Inter-station distances varied from 37 to 111 km, being mainly between 50 and 80 km. Average distance was 61 km. The coordinates of the network were computed by Geotrim Ltd. with Trimble Total Control from several days of GPS data. The network was fixed to the EUREF-FIN coordinates of the FinnRef stations. The VRS test field within the GPSNet.fi network consists of 15 benchmarks from the EUREF-FIN frame and its densification (small triangles in Figure 2). Distances to the nearest VRS reference station varied between 2 and 50 km.

2.2.3 Static test field

Static test was performed with data from the Finnish permanent GPS network FinnRef and from regular GPS campaigns where antennas were mounted on concrete pillars. These campaigns include data from GeoSatakunta and Olkiluoto deformation study areas. Also data from Suurupi permanent GPS station in Estonia was used in the test. Total of 31 stations or pillars were used in the test resulting baselines between 0.6 and 1,069 km (Figure 3). The ITRF2000 coordinates of the points were determined with Bernese 4.2 using at least 24 hours of data. The epoch of the coordinates is 2004.5 that is the mean epoch of the data used in the test. Standard errors are in the order of few millimetres.

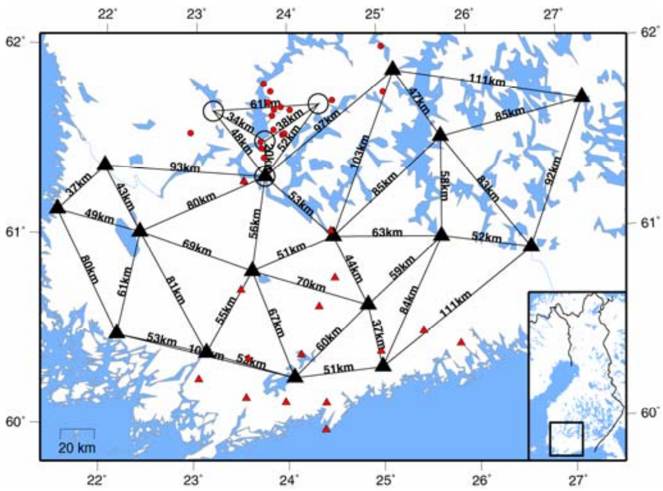

Fig. 2. *The VRS networks and test points used in VRS test. Reference stations of the GPSNet.fi network are illustrated with big triangles and Tampere region with open circles. Associated test points are shown with smaller similar symbols.*

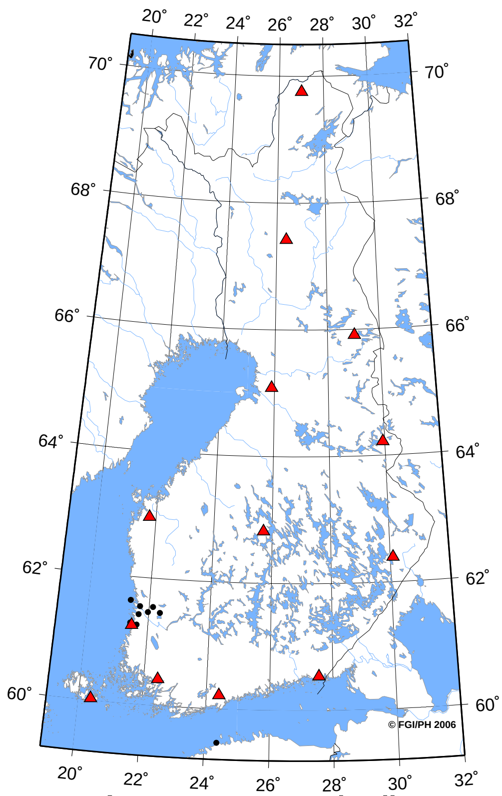

Fig. 3. *Points used in static test. Triangles illustrate FinnRef stations and small circles in Western Finland pillars in Olkiluoto and GeoSatakunta deformation study areas.*

2.3 On hierarchy of the reference frames

Nowadays, in the GPS era, traditional coordinate hierarchy has blurred and direct connection between control points may be missing. In this study different GPS modes are compared to each other. However, the tests have been performed in different networks and test fields (Figure 4). In all cases FinnRef defines the highest order in class hierarchy offering either EUREF-FIN or ITRF reference coordinates. VRS test points belong to 100-point EUREF-FIN coordinate frame, EUREF-FIN densification and II and III order GPS networks of Tampere. The tests have also been carried out in two detached VRS networks, so results belong to hierarchically many different levels. The direct link between the networks may be missing and FinnRef may be the only existing connection. This leads to an unhomogeneous reference coordinate set due to error accumulation and different network adjustments. (Häkli and Koivula, 2005).

Coordinates of the RTK test field instead were computed as one project and tied directly to FinnRef. Therefore they have very precise and homogenous set of EUREF-FIN coordinates at one class hierarchy level. (Häkli and Koivula, 2005). This applies to static test field as well where ITRF2000 coordinates were used instead. For this study, the coordinates of the concrete pillars at Posiva and Geosatakunta areas were determined in one adjustment where Finnref coordinates were kept fixed to their ITRF values.

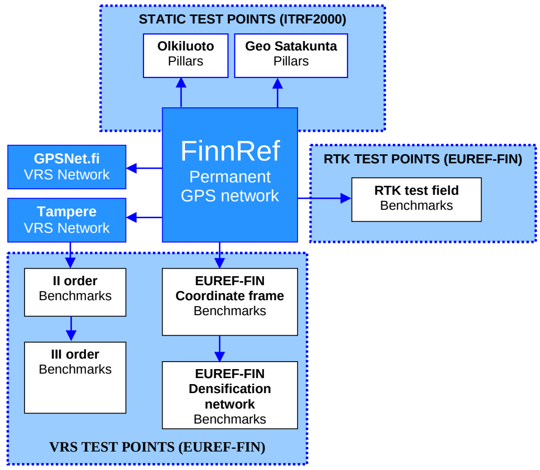

Fig. 4. *The network hierarchy of the reference points. FinnRef serves as the highest order network. Static and RTK test fields are tied directly to FinnRef in one adjustment while VRS test fields consist of existing points belonging to many different networks. Tests done in the VRS network of Tampere include all hierarchy levels except EUREF-FIN coordinate frame in box "VRS test points" while measurements in GPSNet.fi network include reference points from EUREF-FIN coordinate frame and its densification.*

Since the quality of test fields differ from each other, it leads to an unequal starting point in inter-comparison. However, class hierarchy is reality in practical work. This has to be taken into account when the accuracy of the GPS mode is defined. In this study the intention was rather to study the practical than theoretical accuracies.

3 Real-time surveying

3.1 Test methods

Test methods were planned to minimize all non-GPS related error sources. This was already taken into account in test point selections. Test points were to cover the whole operational area of the GPS mode and without unnecessary negative GPS site effects. Observations were planned to give a reliable picture about the quality of the method and therefore e.g. each RTK and VRS observation has an independent ambiguity resolution. For statistical analysis 20 observations were taken at each point and time. Every test point was measured 3-4 times under different satellite geometry resulting in over 2,100 VRS and 1,400 RTK observations. In the rover end the antenna was attached to two-meter long supported pole. Cut-off angle of 15 degrees was used to avoid site effects caused by obstacles at low elevation angles. (Häkli and Koivula, 2005).

During the RTK test five points were chosen as the base stations. At four base stations a tripod and tribrach with optical plummet were used. At METB point the antenna was mounted on concrete pillar. Five test (rover) points were measured using each base station in turns. This way the baselines between 0.4 and 25 km were covered. The VRS test points were chosen to cover the operational area of VRS with 5 km gaps from the closest reference station both inside and outside the VRS network. The farthest point outside the VRS network was 50 km away. (Häkli and Koivula, 2005).

3.2 Results

In order to visualize the results all the VRS and RTK results are shown as North and East components on Gauss-Krüger projection. Heights are ellipsoidal heights. All the measures of accuracy are given with respect to the reference coordinates.

When the test results are compared it is important to remember that the reference coordinates are determined in different ways. Our RTK test field is homogenous, from one coordinate class only. RTK measurements may have a high precision in a frame defined by the base station and satellite orbits but the accuracy may be worse since all the errors in the base station coordinates are systematically included in the measured coordinates as well.

In case of VRS the reference coordinates of the test points are from hierarchically different networks of the FGI and Tampere. There is no straight link between the lower order points of Tampere and the FGI and the only link is FinnRef (see Figure 4). By using test points from different hierarchy levels an additional error may be seen because of error accumulation. On the other hand this feature can be associated to any nation wide coordinate frame that is hierarchically measured. Hence, this same effect is seen if e.g. the coordinates of the first and fifth class points are compared to each other. Nowadays VRS enables to measure local points straight to the highest class while traditionally local points are measured through many hierarchy levels. This means incompatible results between different measurement methods and times.

As in the case of RTK, the reference station coordinates of VRS network are in a key role since they have an explicit influence on measured coordinates (Häkli, 2006). However, the network solution behind VRS method diminishes the possibility of coarse errors. The VRS reference network also guarantees homogeneous results for all surveyors.

The results shown here represent the accuracy in relatively good observation conditions. The tests are based on an extensive material that covers measurements at good GPS surroundings and under different satellite geometries. If measurements are done in the forestry or urban areas where the satellite visibility is poor, the surveyor needs to accept worse accuracy. In the worst case the measurements are not possible at all.

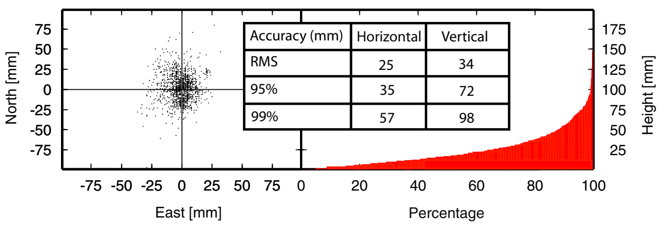

Fig. 5. *Accuracy of RTK.*

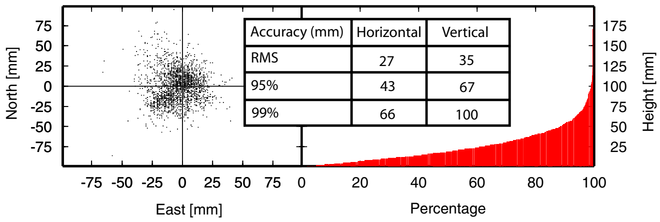

Fig. 6. *Accuracy of VRS.*

3.2.1 Accuracy

Accuracy measures presented here are to give an overview of the capability of the method. They are presented both visually and by statistical analysis. Figures 5 and 6 show the horizontal and vertical accuracies of RTK and VRS. The left-hand side plots illustrate horizontal accuracies. In both methods the horizontal results are equally distributed around the reference coordinates i.e. both methods give results free from systematic errors. Vertical accuracies (right-hand side) are similar and mainly better than 10 cm.

Accuracies by means of rms, 95th and 99th percentile (tables in figures 5 and 6) show no significant difference between RTK and VRS. The horizontal accuracy of VRS (43 mm, 95%) is slightly worse than of RTK (35 mm) but some of this difference may be related to hierarchy of the test points. However, the results indicate that both methods are applicable to measurements with a required accuracy between a few centimetres and a decimetre. (Häkli and Koivula, 2005).

3.2.2 Distance-dependency

Distance-dependent errors were tested with evenly elongated baselines. Baseline lengths varied in RTK tests from 0.4 to 25 km and in VRS tests from 2.4 to 50 km. Although the accuracies by means of rms and 95th and 99th percentile were similar, differences in spatially correlated errors are significant. Distance-dependency was studied by fitting a regression line through the results. Figure 7 summarizes the accuracies of both RTK and VRS with respect to the distance to the reference station. The accuracy of RTK in horizontal direction is ±(9 mm + 0,6 ppm) and ±(5 mm + 1,7 ppm) for the height. Equivalent values for VRS are ±(19 mm + 0,1 ppm) for horizontal and ±(14 mm + 0,5 ppm) for vertical coordinates. The regression lines are converging at the distance of 18.8 km for horizontal and at 7.9 km for vertical accuracies. Further away from the reference station VRS gives better results.

The constant part of error (*b*) for RTK seems to be less than half of VRS's (see also Table 1). However, it seems unlikely that such a difference would be caused by superiority of RTK as a system since VRS has more sophisticated error estimation. Expectations would be that the constant parts are similar or even slightly better with VRS. Thus, it seems more likely that this difference is caused by other phenomena. The most likely cause is the reference coordinates used in the tests. VRS had an unhomogeneous set of reference points while RTK had one very precise test field (see chapter 2.3). However, this is a common problem and therefore VRS results give a realistic picture of the accuracy in practice. RTK, instead, gives results with respect to the base station coordinates without the knowledge of possible systematic errors in the reference coordinates. In our study the constant part was small due to very precise test field. However, based on the results, we can conclude that both methods work fine within their operational area. The operational area however is much larger in case of VRS.

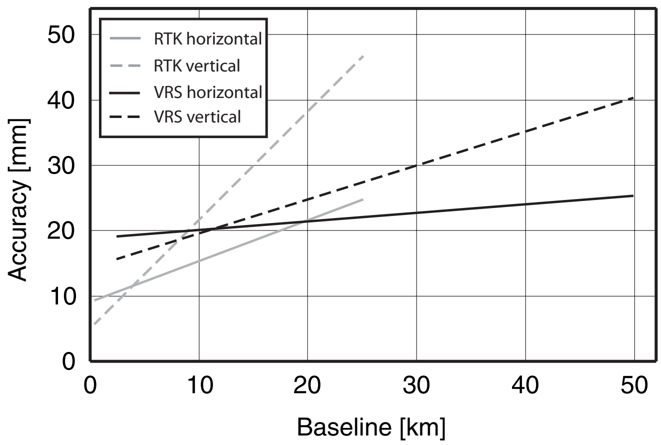

Fig. 7. *Distance-dependent errors of RTK and VRS within their operational area. Distance-dependencies of RTK are shown with grey and VRS with black lines. Solid lines illustrate horizontal and dashed lines vertical accuracies.*

Table 1. *Distance-dependency of RTK and VRS and error estimates (1σ).*

		b **(mm)**	***a*** **(ppm)**
RTK	Horizontal	9.4 ± 0.9	0.63 ± 0.07
	Vertical	5.4 ± 1.1	1.66 ± 0.08
VRS	Horizontal	18.8 ± 0.7	0.13 ± 0.03
	Vertical	14.4 ± 1.0	0.52 ± 0.04

4 Static surveying

4.1 Test methods

4.1.1 Data and baseline processing

Aim of the static test was to find dependency between session duration, baseline length and accuracy. Therefore static data of the test was to cover wide range of baseline lengths and session durations. Baseline lengths were between 0.6 and 1,069 km with session lengths varying between 10 min and 24 hours. These scales were considered to fulfil the requirements of conventional static GPS surveying. The data was collected from the Finnish permanent GPS network, FinnRef, and from regular GPS campaigns, where antennas were mounted either on steel masts or concrete pillars. Therefore data is expected to be free from centring and height reading errors. The set of baseline data is a random sample from all the data from several GPS campaigns in 2003-2004. This way it was to give a realistic picture about the variations e.g. in annual and daily periods of GPS. Reference coordinates for the stations were computed for the mean epoch (2004.5) of the test data in ITRF2000. This ensures homogeneity of the reference coordinates.

The data was processed with commercial GPS software (Trimble Total Control) using standard processing parameters. These were mainly default options of the software. NGS antenna models were used for the processing. Results are presented for individual baselines i.e. adjustments were not applied. In general, accuracy is expected to improve if proper network adjustment is utilised. Total of 5,000 baselines were processed for the study with broadcast ephemerides.

4.1.2 Pre-processing of the baseline results

In order to find the correlation between baseline length, session duration and accuracy, a surface fit for the baseline results was done. To find the optimum data set for the surface fit, results were pre-processed. One data set can be considered as one grid point consisting approximately of 20 baseline results. At first, a simple pre-elimination of gross errors was performed. Errors greater than 0.5 m for individual baseline were considered to be gross errors and they were eliminated from the results. According to the normal distribution, all data points outside the 99,9% (approximately 3σ) deviate significantly from the rest of the data and therefore they can be considered as gross errors. Hence, with an assumption that the data sets are normal distributed, we rejected also data points that deviated more than 3σ from the average of each data set. After this we computed 95th percentile for each grid point.

4.1.3 Surface fit

After the grid data was pre-processed we used a multiple regression to fit a surface to the results. Several different surfaces were tested for the data sets. Since the grid is not evenly spaced and data is varying, we ended up fitting a plane to the logarithmic scales and to the square root of 95th percentiles. The formula is presented in equation 1. Plane was fitted iteratively with the least squares method. We computed the fit errors ($e_i = z_i - Z_i$) and if they deviated more than $3\sigma_e$ they were rejected with iterative process. Iterations were continued until all outliers were rejected.

Equation 1. Formula used for the surface fit.

$$\sqrt{z} = a + b \cdot \log(x) + c \cdot \log(y)$$, where

x	baseline length [km]
y	session duration [h]
z	95th percentile of accuracy [m]
a, b, c	coefficients of surface fit

4.2 Results

Figure 8 shows the connection between baseline length, session duration and accuracy (95th percentile in 3D) when broadcast ephemerides are used. Regression lines (plane) are drawn according to the equation 1. Coefficients of the surface fit were determined with 16 iteration rounds of least squares fit. As a result following coefficients were obtained with certain constraints. Coefficients and the formula are valid only for the given ranges.

$$a = 0.051 \quad b = 0.122429 \quad c = -0.086042 \quad \text{if} \quad \begin{array}{l} (x = [1, 1000],\ y = [0.17, 24], z = [0.01, 0.05]) \text{ or} \\ (x = [1, 1000],\ y = [0.5, 24],\ z = [0.05, 0.10]) \end{array}$$

49 grid points were rejected during the iteration process. This number is relatively high (18,35%) but rejected points are mainly caused by too short session duration for the baseline to be measured. These cases show the borderline where GPS solution gets radically weaker and should not be used for the fit. For this reason regression lines are not drawn all the way in the figure but are cut from certain points. Also some data is missing deliberately since for basic surveying it is no worth of computing e.g. baselines of few kilometres with 24-hour sessions or baselines of 1,000 km with 10-minute sessions. Due to these constraints graph, formula and coefficients are not valid outside the operating area. Operating range for the accuracy (95%) is 1…5 cm for the session durations 10 minutes to 24 hours and 5…10 cm for the session durations from half an hour to 24 hours. Baseline length must be within the range of 1…1,000 km. Extrapolated values out of these ranges may be coarsely erroneous. Interpolation within the operating ranges instead is allowed. One may use graph to estimate the third variable if two other are known. We drew regression lines for 1, 2, 5 and 10 cm accuracies (95%) to the figure 8.

Rms of the final fit is 21 mm while it was 55 mm before the iteration rounds. Rms is relatively good for this kind of data set with large deviations. Rejected data sets during the iteration process are mainly outside the operating area of the formula and may be coarsely erroneous. Such errors occur when session duration is short and baseline is long. Goodness of fit (R^2=0.84) proves the suitability of the regression model for this data set.

While using the graph or formula one must remember that all resulting values are only estimates and one's own results may be strongly dependent on other factors e.g. measurement conditions, environment, used software and parameters just few factors to mention. Also, the graph and formula give the accuracies for independent baselines, so one may expect better results with proper network adjustment. Another thing to consider is that for longer baselines it might be advisable to use precise orbits instead of broadcast ones. Results shown here, give the accuracy only for broadcast orbits.

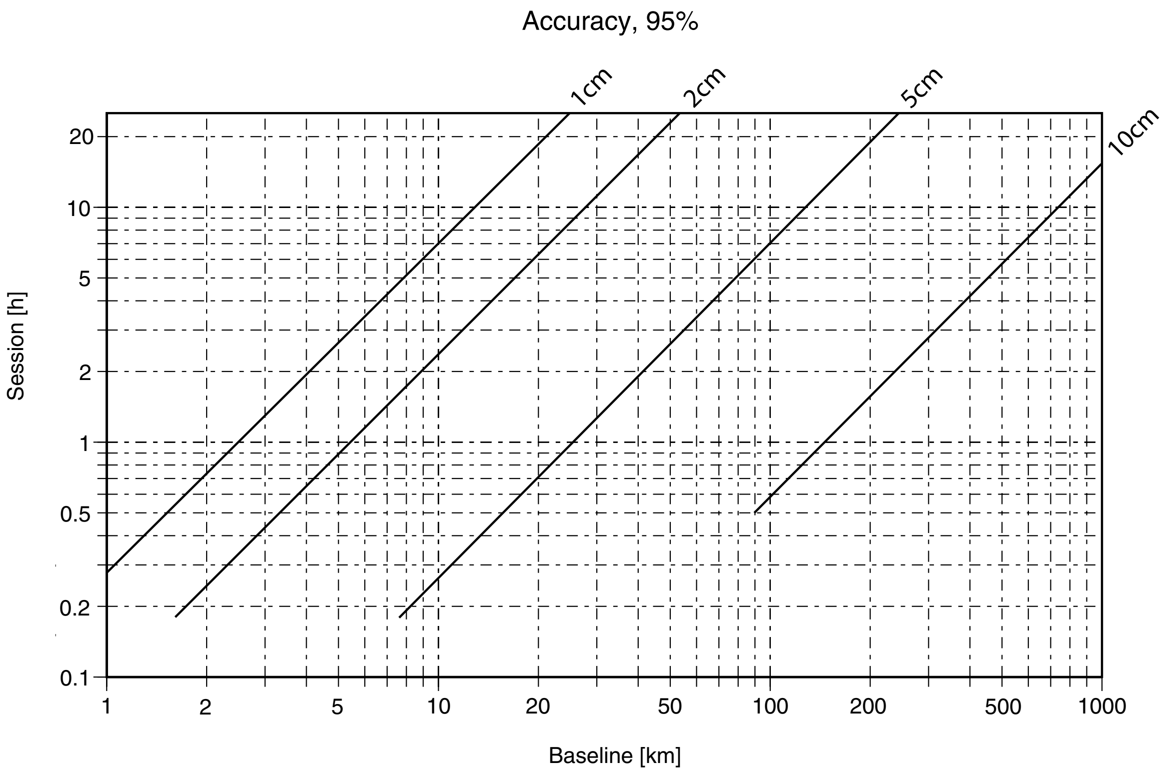

Fig. 8. *Static GPS results for individual baseline solutions with broadcast ephemerides. Dependency of baseline length, session duration and accuracy (3D, 95%). Regression lines are for accuracies of 1, 2, 5 and 10 cm.*

5 Discussion

VRS and RTK give relatively similar accuracies. Typically the accuracy of GPS is given with constant part and additional distance-dependent part. The accuracy of RTK in horizontal direction is ±(9 mm + 0,6 ppm) and ±(5 mm + 1,7 ppm) for the height. Equivalent values for VRS are ±(19 mm + 0,1 ppm) for horizontal and ±(14 mm + 0,5 ppm) for vertical accuracies. This study indicates that RTK gives better accuracy over short distances. This result originates from the class hierarchy of the test points. RTK test points were from one hierarchy class only when VRS test points were from several classes by FGI and Tampere. This leads to an erroneous conclusion if only theoretical accuracy is studied, but since in reality the surveyors need to measure within different coordinate classes this gives a realistic result on expectable results. Such systematic error may be diminished with local transformation that takes into account local coordinate distortions.

In any real-time GPS application it is essential that the coordinates of the base station or reference station are of high quality. Hence, it could be recommended that RTK base stations are as high order as possible and then apply local transformation for the results if needed. Another option is to use reference points on the same or one higher class than the desired coordinates. This way the local systematic errors will be included in the results and the measured coordinates fit better to the surrounding coordinates of the same class. This however, may in some cases influence on the success of measurements.

For static GPS we give results showing the relation between accuracy, session length and baseline length. These results are based on intensive dataset of 5,000 baselines. With graph or formula presented here one can estimate one of above-mentioned variables if two of them are known. However, while using the graph or formula one must remember that all resulting values are only estimates even if they describe this data set well. Surveyor's own results may be strongly dependent on other factors e.g. measurement conditions, environment, used software and parameters. Another important thing to remember is that the graph and formula give the accuracies for independent baselines, so one may expect better results with proper network adjustment. Also usage of precise orbits should produce better accuracy. Results shown here, give the accuracy only for broadcast orbits but the study will continue with the same test with precise ephemerides.

Acknowledgements

Geotrim Ltd. and City survey of Tampere are acknowledged for the licences to use their VRS services and other valuable assistance during the study. Several people have supported our measurements. We wish to thank Carmen Cobalas (University of Stuttgart), Heli Suurmäki and Veikko Saaranen (Finnish Geodetic Institute) for assisting during the VRS measurements; Thomas Seiss, Carina Raizner and Alexander Fietz (University of Stuttgart) for their efforts during the RTK test. Inese Evele (Riga Technical University) has done a huge work by processing part of the static GPS baselines and is greatly acknowledged by the authors. We are also grateful to our colleagues at FGI for valuable comments.

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The Nummela Standard Baseline – a world-class length standard

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Geodetic metrology is an essential field of research in the Finnish Geodetic Institute, including e.g. gravimetry, precise levelling techniques, precise length measurements and quality of GPS measurements. As prescribed in the Law no. 581/2000, the Finnish Geodetic Institute maintains standards for measurements in geodesy and photogrammetry, and is the National Standards Laboratory of Length and Acceleration of Free Fall. As a National Standards Laboratory the Finnish Geodetic Institute is a participant in the Mutual Recognition Arrangement (MRA) by the BIPM. Our quality management system meets the requirements of ISO/IEC 17025 and ISO 9001 standards. Recent research and development related to our foremost length standard, the Nummela Standard Baseline, are briefly presented here.

Fourteen interference measurements

Unique measurement method, long history and excellent stability make the Nummela Standard Baseline a world-class standard in length metrology. Works at Nummela comparison baseline were started in 1933, when comparisons of invar wires were moved from Santahamina in Helsinki to Nummela. Since the first measurements with the Väisälä white light interference comparator in 1947 the place has been called the Nummela Standard Baseline. Between 1947–2005 14 interference measurements have been performed. The length between the underground markers, 864 122.8 mm, has varied less than 0.6 mm since 1947, and all standard uncertainties of remeasurements are smaller than 0.1 mm (Table 1).

New working premises

In 2004, the two dilapidated buildings from 1933 were pulled down and replaced by a new baseline store and office building (Fig. 1). Essential parts of the baseline were fenced and all the observation pillars were roofed (Figs. 2–4). Now reconditioning of pillar structures is about to begin. Also replacing the Kern forced-centring systems with more versatile constructions is under consideration.

Väisälä interference comparator

A 1-m-long quartz gauge determines the scale of the baseline. The length is multiplied to lengths between mirror surfaces on observation pillars using the Väisälä interference comparator. Projection measurements with precise transferring and plumbing and angle measurements are needed to determine the more permanent lengths between underground markers.

The method, developed by Yrjö Väisälä in the 1920s, is still the most precise in length metrology for lengths shorter than 1 km. The principle is simple, but implementation is laborious and needs extremely stable environmental and weather conditions. Building up and adjusting the comparator on the observation pillars takes a couple of weeks, and interference and projection observations may take a couple of months. Just one or two degrees temperature changes are allowed during one measurement, which takes several hours. Usually this is possible only in a few cloudy autumn nights. Nummela is one of the few places in the world, where these measurements are performed.

At Nummela we use the quartz gauge no. VIII, the length of which (about 1.000 151m) is known with ±35 nm standard uncertainty from laboratory measurements in PTB Braunschweig, MIKES Espoo and Tuorla Observatory of University of Turku. We multiply it up to 864 m (2 x 2 x 3 x 3 x 4 x 6 x 1 m). In autumn 2005, we succeeded seven time up to 432 m. New attempts for 864 m will be made in near future, after reconstruction of the old observation pillars.

Table 1. *Lengths between underground benchmarks with standard uncertainties.*

Epoch	0 – 24 mm + 24 m	0 – 72 mm + 72 m	0 – 216 mm + 216 m	0 – 432 mm + 432 m	0 – 864 mm + 864 m
1947.7	—	—	—	95.46 ±0.04	122.78 ±0.07
1952.8	—	—	—	95.39 ±0.05	122.47 ±0.08
1955.4	—	—	—	95.31 ±0.05	122.41 ±0.09
1958.8	—	—	—	95.19 ±0.04	122.25 ±0.08
1961.8	—	—	—	95.21 ±0.04	122.33 ±0.08
1966.8	—	—	—	95.16 ±0.04	122.31 ±0.06
1968.8	—	—	—	95.18 ±0.04	122.37 ±0.07
1975.9	—	—	—	94.94 ±0.04	122.33 ±0.07
1977.8	33.28 ±0.02	15.78 ±0.02	54.31 ±0.02	95.10 ±0.05	122.70 ±0.08
1983.8	33.50 ±0.02	15.16 ±0.02	53.66 ±0.04	95.03 ±0.06	—
1984.8	33.29 ±0.03	15.01 ±0.03	53.58 ±0.05	94.93 ±0.06	122.40 ±0.09
1991.8	33.36 ±0.04	14.88 ±0.04	53.24 ±0.06	95.02 ±0.05	122.32 ±0.08
1996.9	33.41 ±0.03	14.87 ±0.04	53.21 ±0.04	95.23 ±0.04	122.75 ±0.07
2005.8	**33.23 ±0.04**	**14.98 ±0.04**	**53.20 ±0.04**	**95.36 ±0.05**	—

Fig. 1. *The new main building.*

Fig. 2. *The Väisälä comparator house.*

Fig. 3. *The shelter for observation pillar and underground marker at 864 m.*

Fig. 4. *Calibration of a tacheometer.*

Fig. 5. *Comparison of quartz gauges at the Tuorla Observatory of University of Turku.*

Fig. 6. *Adjusting the quartz gauge in the Väisälä interference comparator.*

Traceability

The measurements at Nummela are traceable to the definition of the metre. The latest absolute calibration of quartz gauges was performed in year 2000 in MIKES with an interferometrical equipment for gauge block calibration.

Relative comparisons are performed before and after every interference measurement in Tuorla. The quartz gauge system, now BTM00, has been maintained using interferometrical comparisons for more than 70 years. Since 2005 the Finnish Geodetic Institute is responsible for the most part of these measurements at Tuorla and of maintenance of the system. We performed the latest comparisons in April and December, 2005 (Fig. 5). The new results fit well with the previous time series.

Using the quartz gauge system, Väisälä interference comparator and Nummela Standard Baseline (Fig. 6) the traceability chain extends from the definition of the metre to practical applications such as calibration measurements and further applications.

Applications

The baseline is used in calibration, research and testing of the most precise electronic distance measurement (EDM) instruments in field conditions, independently of other calibration methods. Fifteen different distances 20–864 m are available. For velocity corrections, air temperature, pressure and humidity are measured with calibrated psychrometers and barometers. Even in precision instruments significant scale and constant errors are common.

The scale has been traceably transferred using the Väisälä comparator and/or Nummela Standard Baseline to a number of baselines around the world, during the last ten years to Lithuania, Taiwan, China, Hungary, Estonia, Norway, Serbia, Japan and South Korea (Fig. 7) and to control networks in deformation analysis (e.g. Olkiluoto and Metsähovi). Only a few instruments, such as Kern ME5000 and some Leica models, can be used as transfer standards; we often use the ME5000 of the Institute of Geodesy of Helsinki University of Technology.

In the international projects calibration baselines and test fields for surveying instruments have been established or maintained; this is co-operation with national mapping authorities. In Japan and South Korea we have participated in preparation of official metrological comparisons of EDM instruments. New instruments based on new femtosecond frequency comb technology are soon expected to challenge the existing precision instruments in future comparisons.

In Olkiluoto (Fig. 8) a control network around the nuclear power plants and final disposal facility has been measured twice a year in GPS observation campaigns since 1995. To compare the irregular and unknown scale variations of GPS measurements with a traceable scale, a 511-m EDM baseline has been simultaneously measured with a Kern ME5000 since 2002. A longer time series will produce material for interesting analyses.

Fig. 7. *Recent scale transfers using the quartz gauge system and Väisälä interference comparator and/or Nummela Standard Baseline to other geodetic baselines.*

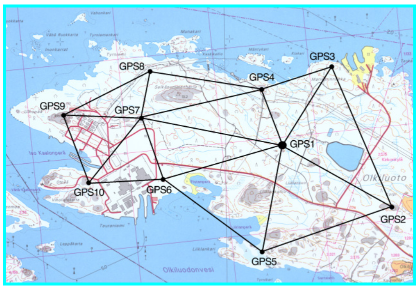

Fig. 8. *The GPS monitoring network at Olkiluoto nuclear power plants. The 511-m EDM baseline is between stations 7 and 8.*

Other small networks for local geodynamical research we have established at Metsähovi research station. Geodetic observation methods there include VLBI, SLR, DORIS, GPS and GLONASS measurements, absolute and superconducting gravimetry and seismometry.

To link the reference points of Metsähovi with each other and to global reference frames, and to monitor possible movements, we perform repeated high precision control measurements. We use precision tacheometry and precise levelling to determine relative positions, and GPS measurements for orientation. Tested and calibrated instruments are essential in this, and regular use of Nummela Standard Baseline is a standard routine. Expected one-millimetre accuracy has been reached.

Another topical research subject at Metsähovi is the precise levelling test field, where a few years of frequently repeated levellings unexpectedly showed obvious seasonal variation of up to several mm in height differences between benchmarks in bedrock. With our tacheometers, regularly tested in Nummela, we have measured possible related horizontal deformations. Sub-millimetre repeatability has been obtained, but with so far no clear evidence of horizontal movement.

An Open Source GPS baseline processor based on GPStk, the GPS toolkit

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VecSol, a GPS vector solver, computes a 3D vector solution using dual-frequency carrier phases. A double difference algorithm is applied with properly computed weights (elevation sine weighting) and correlations. The program iterates to convergence and attempts to resolve ambiguities to integer values if close enough. Crude outlier rejection is provided based on a triple-difference test. Ephemeris used are either broadcast or precise (SP3). Alternatively, also P code processing is provided.

The solution is computed using the ionosphere-free linear combination.
The ionospheric model included in broadcast ephemeris may be used. A standard tropospheric correction is applied, or tropospheric parameters (zenith delays) may be estimated."

Deformation Studies at Ny-Ålesund, Svalbard

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The need for fundamental geodetic stations, as the Space-Geodetic Observatory at Ny-Ålesund, Svalbard, is crucial in maintaining the stability of global terrestrial reference frames. The geodetic infrastructure at the observatory includes a 20-m VLBI antenna, several GPS receivers, a tide gauge, a super-conducting gravimeter and a co-located DORIS station. Repeated absolute gravity measurements complement the observations.

In order to study the stability of the Kings Bay area in Svalbard, a GPS control network was established in 1998 extending in east-west and north-south directions approximately 50 km by 30 km. Several GPS campaigns have been carried out from 1998 to 2005. The data from these campaigns are compared with the neo-tectonic activity in the area. A permanent GPS receiver was mounted in 1991 and an additional permanent GPS receiver was installed in 1997. A comprehensive comparison between the GPS determined three-dimensional velocities from both receivers, VLBI velocities and published ITRF velocities will be presented.

A new high-precision GPS network in Denmark

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Introduction
The National Survey and Cadastre (KMS) will introduce the use of GPS instead of performing future national precise levelling campaigns, because the levelling campaigns are expensive and time-consuming. The introduction of GPS should be done in such way, that it is possible to transfer the height information from the precise levelling network to the new GPS network. Furthermore, it is important to preserve the historical information from the previous three precise levelling campaigns.

KMS is therefore establishing a new national high-precision GPS network consisting of 98 points. Each GPS point is located near a nodal point in the precise levelling network and the GPS point is connected to the nodal point by levelling. Repeated GPS observations of these points in combination with levelling to the nodal points will replace future national precise levelling campaigns. We are aiming at defining a new height system in the future using the GPS observations.

The repeated GPS observations will not only replace the national precise levelling campaigns, the purpose of the GPS network will also be to observe both horizontal and vertical regional land displacements and to separate vertical land displacements from mean sea level changes. The latter will also require levelling from selected GPS points to tide gauge bench marks.

Fig. 1. *Levelling lines of the third precise levelling from 1982 to 1994.*

The time series for each GPS point will contain geographical coordinates φ and λ, ellipsoidal height h and height above mean sea level H. Furthermore, relative gravity measurements Δg will be performed at each GPS point. In this way we have 5 types of information (5 "dimensions") for each point and the new network is therefore called "5D" network.

Network in two phases
The establishment of the network is divided in two phases due to the EUVN Densification Action project (EUVN_DA). Phase 1 (fig. 2) is the Danish contribution to the EUVN_DA project. Phase 2 (fig. 3) is a densification of phase 1, which is necessary to fulfill the purpose of the network.

The EUVN_DA project wishes to receive GPS coordinates and levelling heights for points with a spacing of 50-100 km. We selected 39 suitable nodal points in the precise levelling network (which gives a spacing of max. 50 km) and established a new GPS point or used an existing GPS point if possible near the nodal point.

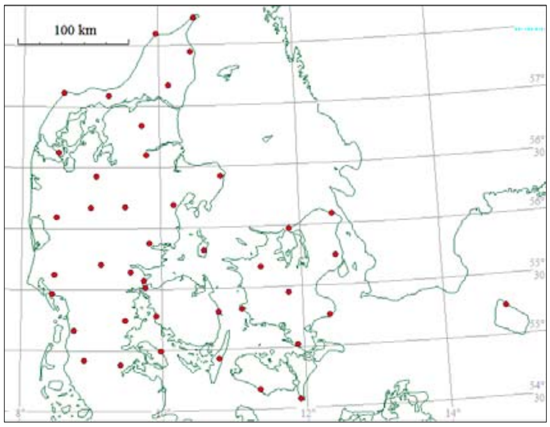

Fig. 2. *Phase 1, 39 GPS points which are also used for the EUVN_DA project.*

The points in phase 1 were established and measured with GPS and levelling in 2004. In 2005 and 2006 we are establishing and measuring the points in phase 2, which consists of 59 new-established or existing GPS points. All 5D points are shown in fig. 4.

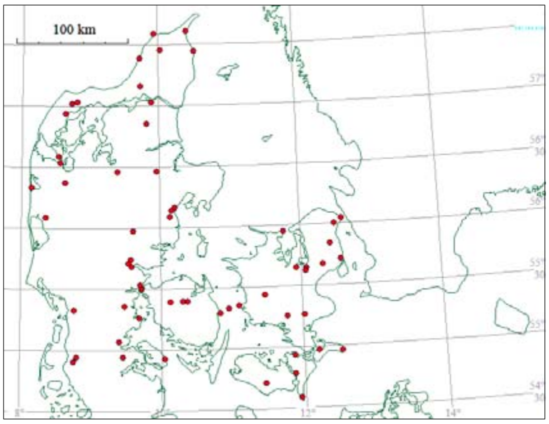

Fig. 3. *Phase 2, 59 GPS points.*

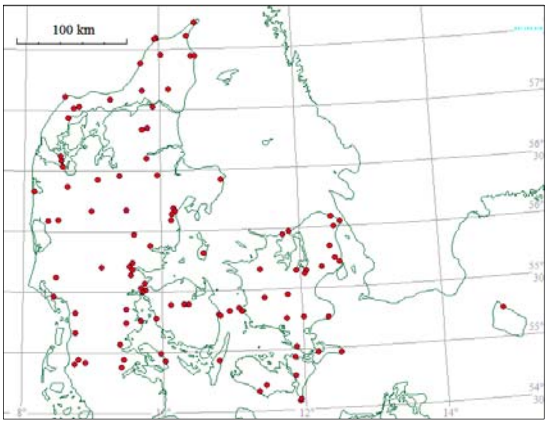

Fig. 4. *Phase 1 and 2, 98 GPS points.*

Levelling

Most of the levelling points are established with a 0,3 x 0,3 x 1 m concrete pillar about 1 m below terrain in a well of concrete and with a cover of concrete.

The levelling nodal point, which connects the GPS point with the precise levelling network, is actually not only one point but a group of two or three points in order to strengthen the connection from the precise levelling network to the GPS network and to monitor the internal stability of the local levelling points and the GPS point. These points are tied together by a local levelling network of high precision.

Levelling will also be performed between tide gauge bench marks with long sea level time series (>100 years) and the nearest GPS point. These tide gauge bench marks are the same as those used for the definition of the Danish national height system DVR90.

GPS observations

Both new and existing GPS points are established with a 1,5 m iron screw peg. It is established about 50 cm below terrain in a well of concrete and with a cover of concrete (fig. 5).

Each GPS point is observed for at least three full 24 hour sessions. A group of four to five GPS points are observed simultaneously, which can be performed by one man alone during an ordinary working week. The GPS instruments are set up on Mondays and taken down on Fridays. Neighbouring groups are overlapping by one point, which means that we have a coherent network covering the whole country. Our plans are to re-measure the GPS points including levelling to the nodal point after 5-10 years.

Fig. 5. *Point marker for GPS points.*

Gravity measurements

The relative gravity measurements on each GPS point are carried out in order to provide all the GPS stations with a complete set of information. In general gravity is needed to convert levelled height differences into differences of geopotential numbers. With these measurements it is possible to calculate geopotential numbers for the GPS points if necessary. The relative gravity measurements are connected to absolute gravity stations observed in 2005 by the Danish National Space Center (DNSC).

At the present time our plans are not to do any future re-measurements of relative gravity because the relative gravity measurements are not accurate enough to reveal land displacements.

Status of measurements and processing

The GPS and levelling measurements are almost finished, only a few points in phase 2 are still missing. The gravity measurements have just started in November 2005 and will continue the next 2-3 years. These measurements are carried out in cooperation with DNSC, which will also do the processing of the gravity data.

Since the GPS point is connected to a group of levelling points a special strategy is needed in order to transfer the DVR90 level from the levelling network to the GPS network, i.e. we will take into account if the GPS point and the levelling points prove to be internal unstable. We are developing the strategy in cooperation with DNSC and it is still under consideration.

The processing of the GPS data will be done with Bernese 5.0. We will connect the stations to the ITRF2005 solution when available. The GPS observations are carried out during a period of 2 years and if we wish to refer to a common epoch we have to transfer the coordinates to this epoch. A method for this is not fully decided yet.

Site dependent error sources in groundbased GNSS networks

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GNSS observations from groundbased networks of receivers are used for high precision positioning. Estimated water vapour parameters from GNSS observations are also implemented in numerical weather prediction. Even though the precision of the position and water vapour estimates are of high quality unmodeled errors often still exists. One remaining error source is related to the GNSS antenna and its interaction with the local environment at a site. The location of the phase centre, i.e. the point of signal reception, of a GNSS antenna varies with the direction and frequency of the incoming signal. Thus, knowledge of such phase centre variations are important for applications demanding high precision. The phase centre variations for most GNSS antennas used in high-precision applications are known from calibrations carried out by the various manufacturers or by the International GPS Service (IGS). However, the phase centre variation of antennas may also be significantly affected by the local environment at a site. In order to establish a full calibration of the antenna and its local environment sitetesting is required. In this paper we describe the physical background to this phenomenon and its resulting effects. We also demonstrate the effects by showing results from 6 years of daily GPS-data analysis of SWEPOS data. Results are obtained from different types of permanent GNSS installations. Finally, we also describe methods and results from an attempt to perform site-calibrations.

Geodetic reference frames in the presence of crustal deformations
-with focus on Nordic conditions

Martin Lidberg[1,2], Jan M. Johansson[1,3], Hans-Georg Scherneck[1]

Abstract

We investigate the agreement between the official national realisations of the European reference frame ETRS89 in the Nordic and Baltic area, using a Nordic GPS campaign from the autumn 2003. In this study we focus on the implementation and use of a model for deformations due to the Fennoscandian Glacial Isostatic Adjustment (GIA) process. The national realisations of ETRS89 are performed at different time epochs and no corrections for intraplate deformations have been applied. The national ETRS89 realisations therefore relate to the shape of the earth at different epochs in time between the autumn of 1994 and mid 1999, which for the Nordic area imply a deformation at the 10 cm level in the vertical if compared to the stated epoch 1989.0 for ETRS89.

In order to facilitate the common use of ETRS89 within the European Community it is necessary to maintain ETRS89 as an accurate pan-European high quality geodetic reference frame. This prompts for a clarification regarding the epoch for internal deformation in future ETRS89 realisations.

1. Introduction

The foundation for the development of a uniform high accuracy European Reference Frame (ETRS89 and its realisations) was established when IAG formed the new sub-commission EUREF, and CERCO formed the Working Group VIII on geodesy in 1987. The background was the growing need for geoinformation data in a uniform geodetic reference system for many applications, e.g. surveying, navigation, transportation, and logistics. Important actors were e.g. the car industry and EUROCONTROL (the European Organisation for the Safety of Air Navigation). This forced the survey agencies in Europe to establish a uniform reference frame. The result was the development of the European Terrestrial Reference System 89 (ETRS89) (Adam et al. 2000).

According to its definition the ETRS89 is coincident with the ITRS (International Terrestrial Reference System) at the Epoch 1989.0 and fixed to the stable part of the Eurasia tectonic plate (e.g. Boucher & Altamimi, 1992). The first wide-spread realisation of ETRS89 was the result of the EUREF 1989 GPS campaign including some 90 sites in (western) Europe, known as EUREF 89. The impact of EUREF 89 among the geodetic community was so strong that it for some time slightly confused the terminology between ETRS89, ETRFxx, and EUREF 89 (although well described in e.g. Boucher & Altamimi 1992). Fortunately, this slight confusion seems to now have been sorted out.

ETRS89 has also been recognised at the European authority level e.g. through the “Inspire Architecture and Standards Position Paper” (Inspire 2002), where it is stated that ETRS89 should be used where allowed, with respect to accuracy limits, and together with EVRF2000 for expressing practical (gravity related) heights. The use of ETRS89 is further encouraged e.g. by Resolution 5 of the EUREF Symposium in Vienna 2005; “*The IAG Reference Frame Sub-commission for Europe (EUREF), — considering the widespread adoption of the European Terrestrial Reference System 1989 (ETRS89) within Europe, — encourages NMAs* and National Cadastral Agencies to raise public awareness of ETRS89 as the recommended European system for geo referencing activities.*”

** (NMA – National Mapping Agency)*

In the Nordic countries national realisations of the ETRS89 have been developed during the second part of the 1990s and introduced for national mapping, geo referencing, urban surveying and construction work. Some brief information on ETRS89 realisations in the Nordic countries are given in Table 1.

The different ETRS89 realisations agree well in general, but because they were observed at different epochs, they are

Table 1. *National ETRS89 realisations in the Nordic countries. (e.g. Mäkinen et al. 2003)*

Country	Denmark	Finland	Norway	Sweden
System/campaign	EUREF-DK94	EUREF-FIN	EUREF-NOR94 EUREF-NOR95 EUREF-NOR96	SWEREF 99
Internal epoch	1994-09-15	1997.0	Appr. 1995	1999.5
Based on ITRF	ITRF92	ITRF96	ITRF93	ITRF97
Published in	Frankhauser and Gurtner [1995]	Ollikainen et al. [2000]	Kristiansen and Harson [1999]	Jivall and Lidberg [2000]

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based on different versions of the ITRF, and they represent different epochs of crustal deformation where the Fennoscandian Glacial Isostatic Adjustment (GIA) process introduce deformation at roughly 1 cm/yr. In total, the differences in realisations are up to a few centimetres (e.g. Jivall & Lidberg 2000).

The need for a common Nordic reference frame, e.g in the perspective of Nordic or possibly European positioning services, was recognized at the NKG (Nordic Geodetic Commission) General Meeting in Helsinki 2002, where Resolution No 3 "*recommends the development of a unified ETRS89 reference frame on the cm level for the Nordic area and of formulas for the transformation from such a reference frame to the national realisations of ETRS89, as well as the transformation from ITRF to the unified ETRS89 reference frame*". The NKG GPS campaign 2003 (also recognised as the EUREF-NKG-2003 GPS campaign) between September 28 and October 4, coordinated by the NKG Working Group on Positioning and Reference Frames, was the response to this need. The result is the Nordic, Baltic, and Arctic reference frame **NKG_RF03** where the coordinates are given in ITRF2000, epoch 2003.75 (Jivall et al. 2005 and 2006).

In this paper we investigate the discrepancies between the Nordic ETRS89 realisations as well as their internal accuracy using the NKG 2003 GPS campaign. We also present the NKG_RF03 velocity model and investigate its use in transformation through different paths between the national ETRS89 realisations and the common Nordic frame. Then we present a strategy for reference frame management in e.g. Nordic or European positioning services in the perspective of crustal deformation. Finally we propose a slight modification regarding the regulations for ETRS89 to make it better conform to the de facto situation with current realisations and national implementations of ETRS89.

2. The NKG 2003 GPS campaign

In order to compare the different Nordic ETRS89 realisations, we need a common realisation as a reference. For this we use the results from the NKG2003 GPS campaign (Jivall et al. 2005). The campaign covers the Nordic and Baltic area (Figure 1), as well as Iceland, Greenland and Svalbard and includes 133 stations. Most of these sites are permanent operating GPS stations. But campaign style GPS sites are added especially in Denmark, Latvia and Lithuania.

Observations were performed during seven days in GPS week 1238 (week 40, 2003). GPS analysis employed the GIPSY-OASIS-II, the GAMIT/GLOBK and the Bernese software packages. The result was presented in ITRF2000, epoch 2003.75, and was designated NKG_RF03. The complete work was coordinated by the working group for Positioning and Reference Frames within the Nordic Geodetic Commission (NKG).

3. The NKG_RF03vel velocity model

In order to compare reference frames realised at different epochs in time in an area exposed to significant crustal deformation the different reference frames should be translated to a common epoch of the internal (intraplate) deformation. This means that the coordinates should be transformed in time, and we need a model for these internal deformations.

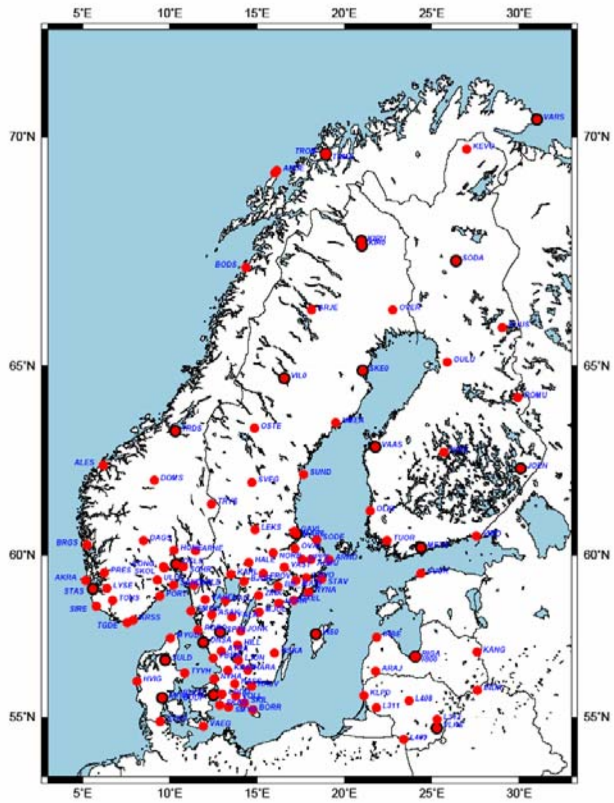


Figure 1. *The Nordic-Baltic part of the NKG 2003 GPS campaign.*

In this study we have used the NKG_RF03vel velocity model, which has been compiled within the NKG Working Group for Positioning and Reference Frames (Nørbech et al. 2006). The intraplate deformation velocities according to this model are shown in Figure 2.

The north and east components originate from the GIA model developed within the framework of the BIFROST effort (Baseline Inferencies for Fennoscandian Rebound Observations Sea level and Tectonics) and presented in Milne et al. (2001). The velocity field of this model has been transformed (rotated) to the GPS-derived velocity field in Lidberg et al. (2006a). Thus, the horizontal velocity field (north and east) describe horizontal displacements relative to stable Eurasia as defined by the ITRF2000 and its rotation pole for Eurasia. In Figure 3 the observed velocities are shown as red (grey) arrows with

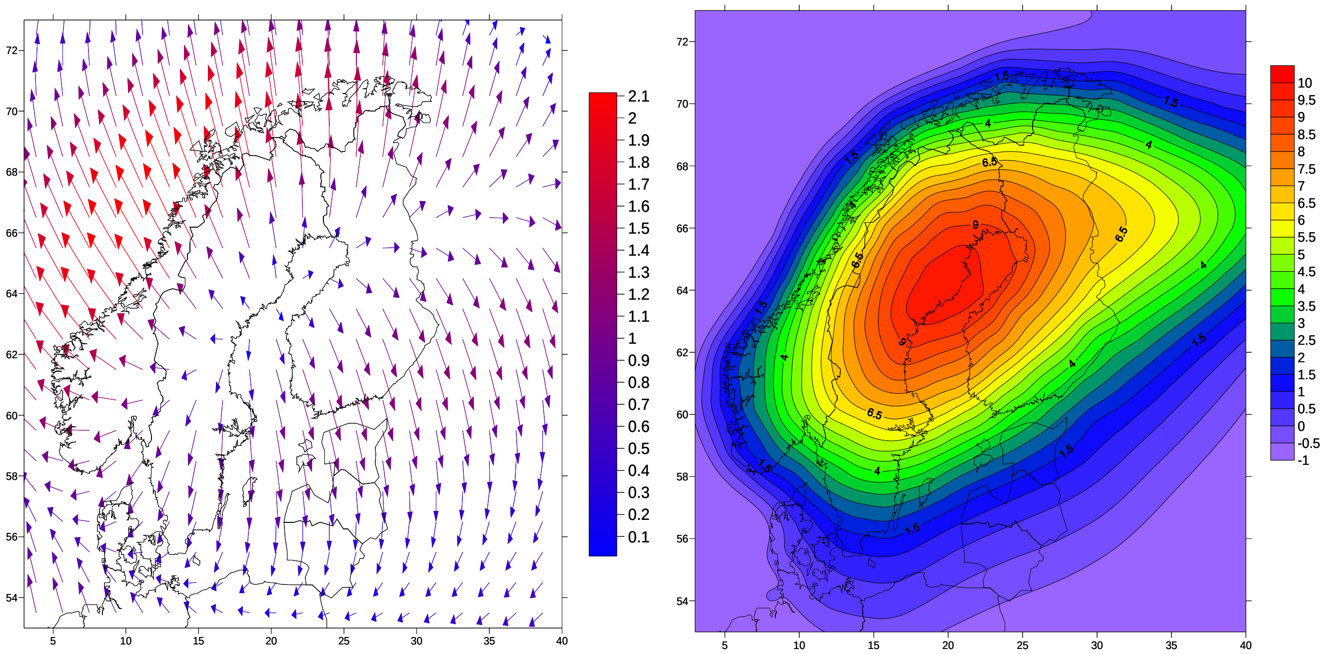


Figure 2. *The NKG_RF03vel velocity model. Reference for the horizontal velocity field (left) is "stable Eurasia" as defined by the ITRF2000 Euler pole for Eurasia. The vertical uplift rates are "absolute" values relative the earth centre of mass (see text). Units: mm/year.*

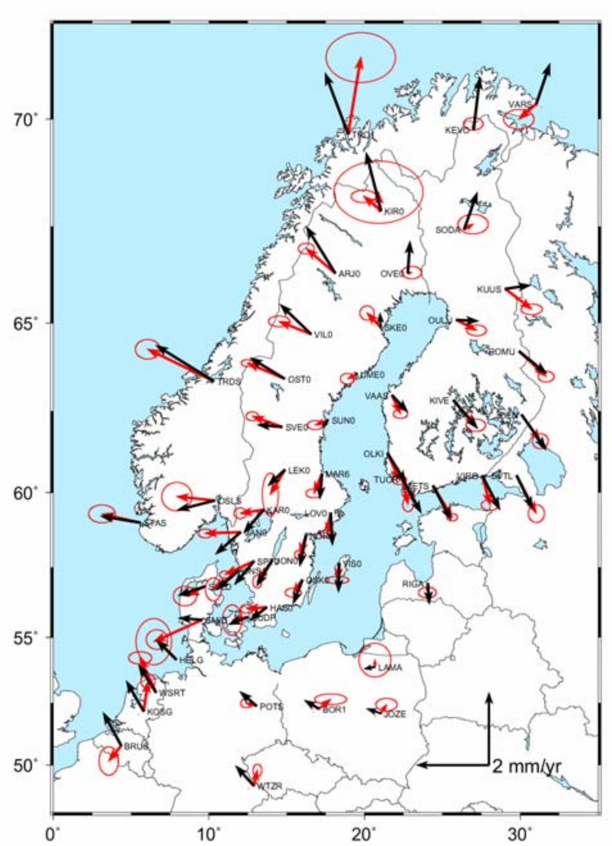


Figure 3. *Observed (red/grey) and modelled (black) horizontal velocities relative to the "stable Eurasia".*

95% error ellipses, and the model transformed to the observations are shown as black arrows. The RMS (root mean square) of the residuals in the transformation is at the 0.5 mm/yr level (Lidberg and Johansson 2005).

For the vertical component, the NKG2005LU(ABS) model (absolute land uplift relative to earth centre of mass), developed within the NKG Working Group for Height Determination, has been used. This model origins from the NKG2005LU(APP) model (apparent land uplift relative to sea level) (Ågren et al. 2006 a and c), which is a smoothed version of a combination of the Vestøl model (Vestøl 2006) used in the Fennoscandia area, and the Lambeck model (Lambeck et al. 1998 a and b) used in the Baltic and northern central European area. The apparent land uplift values in NKG2005LU(APP) have been converted from apparent land uplift values to absolute land uplift with the following formula:

$$u_{abs} = (u_{app} + 1.32 \text{ mm/yr})*1.06$$

Here u_{abs} is the absolute land uplift relative the earth centre of mass, and u_{app} is the apparent land uplift from NKG2005LU(APP). The constant 1.32 mm/year reflects the absolute sea level rise (for this area of the globe) and the factor 1.06 reflects the geoid rise (Scherneck et al., 2003, and Ekman and Mäkinen, 1996).

4. Comparing the official national ETRS89 realizations and NKG_RF03

In the evaluation of the official national ETRS89 realizations, we first computed the coordinate differences to NKG_RF03. In order to arrive at an unbiased result, this comparison requires, however, that NKG_RF03 is translated to the plate tectonic epoch of 1989.0. Therefore, we transformed NKG_RF03 from ITRF2000, epoch 2003.75, to ETRS89 using the official method (Boucher and Altamimi 2001). Additionally we performed a reduction for the intraplate deformations from 2003.75 back to epoch 2000.0. This measure was done to (at least partly) correct for intraplate deformations, reduces the maximum vertical residuals from the 8 cm level to the 4 cm level at some sites close to land uplift maximum (e.g. Lidberg and Johansson 2005). After converting the displacement velocities given in the model NKG_RF03vel as (north, east, up) to the geocentric (X,Y,Z) frame, the corrections for intraplate deformation are applied using the formula:

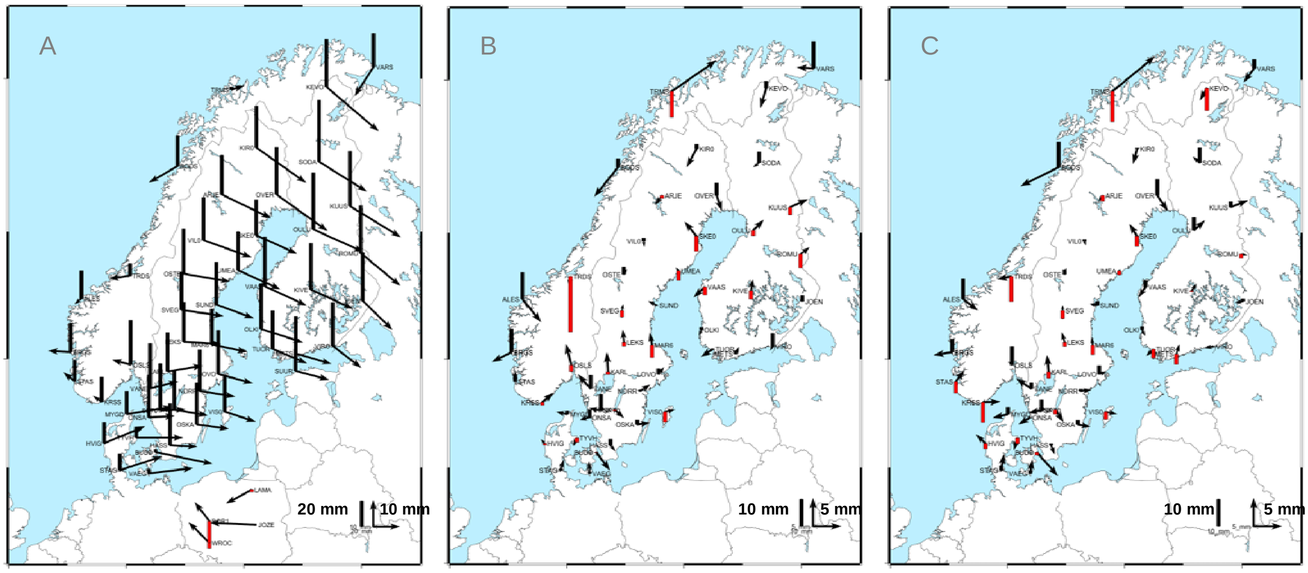
$$\begin{pmatrix}X\\Y\\Z\end{pmatrix}^{ITRF2000}_{EPOCH} = \begin{pmatrix}Y\\Y\\Z\end{pmatrix}^{ITRF2000}_{2003.75} + (EPOCH-2003.75)\begin{pmatrix}\dot{X}\\\dot{Y}\\\dot{Z}\end{pmatrix}^{ITRF/ETRS}_{INTRAMODEL}$$

Here, *EPOCH* is the target epoch, $(\dot{X},\dot{Y},\dot{Z})_{INTRAMODEL}$ are displacement velocities according to the intraplate deformation model (NKG_RF03vel), and 2003.75 is the epoch for the GPS-campaign.

According to the formula, the deformation corrections are applied in ITRF2000 before transformation to ETRS89. Following the ETRS89 memorandum (Boucher and Altamimi 2001), the corrections for intraplate deformations should be applied as a last step after the transformation to ETRS89 (and be reduced back to 1989.0 rather than to 2000.0). We note however that because the orientation differences between ITRF and ETRS89 are small in the view of intraplate deformations, it is not important at which stage the corrections are applied.

In connection to this discussion it must be noted that for the moment (2006) the message from the EUREF technical working group (EUREF-TWG) is that corrections for intraplate deformations should not be applied when creating new realisations of ETRS89 based on campaign style GPS observations. The authors agree on this pragmatic standpoint for most of the European areas where the intraplate deformations are small (<1mm/year level) or difficult to explain by a physical meaningful model. For the Fennoscandian land uplift area the situation is however different since the model can explain some 90-95% of the deformations.

Figure **4A** shows the residuals (first minus second) between NKG_RF03 in ETRS89 and reduced to intraplate deformation epoch 2000.0 and the official national ETRS89 realisations (Table 1). Note that the residual pattern is different and smaller in Norway compared to Denmark, Finland and Sweden. This may be because in ITRF92, ITRF96 and ITRF97 the NUVELL-1a NNR rotation pole was used for Eurasia, while the rotation pole was estimated from the observations in ITRF93 and ITRF2000.



Statistics of residuals
(n,e,u) and (mm)

		n	e	u
A)	Mean:	-3.4	9.8	25.6
	RMS :	6.6	14.1	29.1
B) RMS	Dk:	1.8	1.3	0.9
	Fi:	1.6	1.4	3.1
	No:	3.4	3.6	9.5
	Se:	1.7	1.3	3.1
C) RMS	Dk:	2.5	2.0	1.8
	Fi:	1.3	1.4	3.7
	No:	2.7	3.9	7.5
	Se:	1.5	1.3	2.5

Figure 4. *Residuals between NKG_RF03 in ETRS89 and national realisations of ETRS89; (A) NKG_RF03 reduced to internal epoch 2000.0, (B) NKG_RF03 reduced to internal epoch of each national ETRS89 realisation and national 7-parameter fit, (C) NKG_RF03 reduced to internal epoch 2000.0 and a national 7-parameter fit.*

For Poland we used the values presented by Jarowski et al. (2002) as the official ETRS89 coordinates. These are based on the EUREF-POL 2001 campaign computed in ITRF2001 but then converted to ETRS89 using a 7-parameter Helmert transformation to best fit the result of the EUREF-POL ’92 campaign.

The official coordinates for the station SUUR (Suurupi), Estonia, have been corrected for the reconstruction of the monument in September 1998 using DX = +0.0374 m, DY = +0.1035 m, DZ = +0.0452 m (new minus old), (A. Rudja, and H. Koivula, pers comm.).

Figure **4B** shows in one plot the residuals of the 7-parameter Helmert transformation for each country, when NKG_RF03 are transformed to the national ETRS89 realizations, where NKG_RF03 in ITRF2000, epoch 2003.75, are first reduced for internal deformations to the epoch of the national ETRS89 realizations.

Figure **4C** shows in one plot the residuals for each country when NKG_RF03 is transformed to the ETRS89 with internal deformation epoch 2000.0, and then a 7-parameter fit to each national ETRS89 realization.

The root-mean-square (RMS) values presented in Figure 4 are computed from the plotted residuals (without removing any bias term). In Figure **4A,** the mean value of the residuals are presented, while the mean of residuals in Figure **4B** and **4C** are close to zero due to the applied transformations.

In terms of accuracy, the methods in **4B**, and in **4C** are equal, although there are slightly different residual patterns. It can therefore be argued that it is not necessary to treat the national ETRS89 realisations as different intraplate deformation epochs, but that one can use 2000.0 as the common epoch. The explanation may be that the Helmert transformation absorbs sufficiently well the residual deformation in Norway and Finland that has not been corrected for in **4C**, while the difference in epoch for Sweden (1999.5 and 2000.0 or 0.5 cm level) is of minor importance.

We note the good agreement of the internal geometry between the results of the different GPS campaigns (2 mm level horizontal and <5 mm level vertically – slightly worse in Norway), and 1 cm level and a few cm level for the horizontal and vertical components respectively when comparing the ETRS89 realisations. Also very good and more than sufficient for most (all?) practical applications, we conclude that the challenge is not in how to create a coordinate set with good internal geometry, but how to create a coordinate set based on a well defined reference frame and how to translate this to the ETRS89.

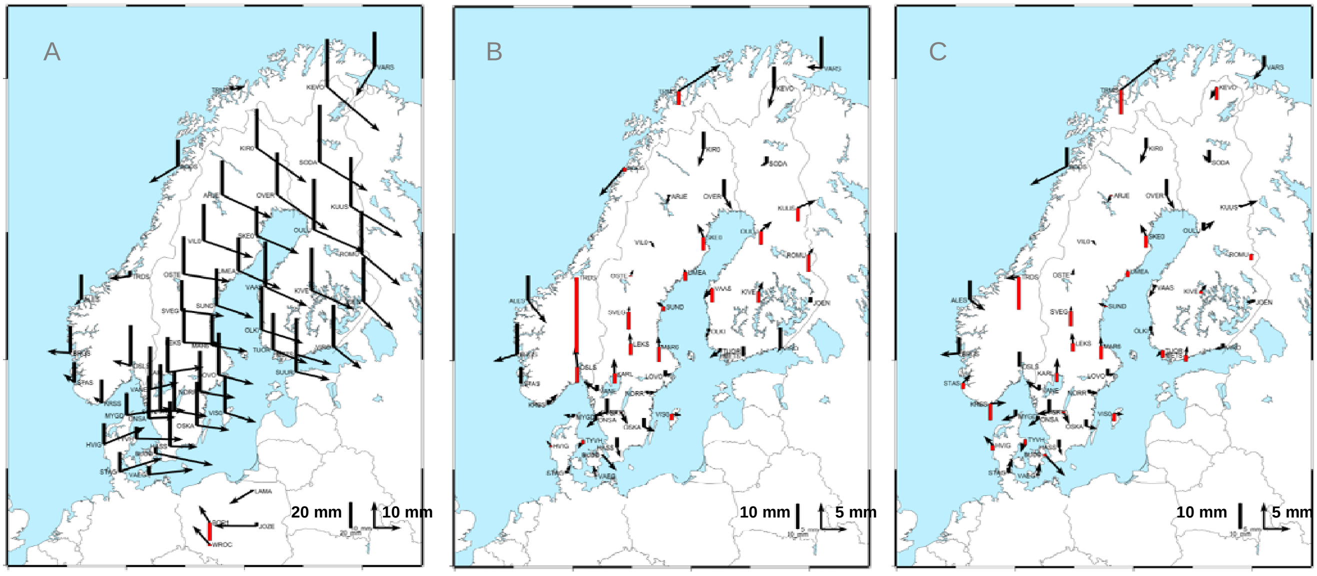
5. An alternative velocity model approach

In adopting a specific model to account for the deformation caused by GIA, we may consider the fundamental difference between using an empirical model deduced from geodetic observations as opposed to using a prediction model based on geophysics and glaciology. In the former case the model will account for additional deformation that is not part of the geophysical model. The latter might be under parameterized and fail to predict significant second order features, and it will be ignorant of other, yet to be identified causes of deformation (tectonic activity to mention one – example: old oceanic crust not isostatically compensated along the Norwegian shelf leading to the development of a subduction zone in the far future). Tuning an intrinsically limited model to observations in order to determine characteristic parameters (viscosities, flexural rigidity of the lithosphere, ice thickness, unloading history, ocean mass redistribution) will inevitably cover up the model’s limitations. On the other hand, an empirical model does not require knowledge of the individual participating subprocesses that cause deformation. On the other hand it will be more sensitive to individual measurement errors and deformation caused by local ground instability.

The model we have used here is a mixed model. For the horizontal part we use internal deformation values from the GIA-prediction model of Milne et al (2001) tuned to GPS-derived station velocities. For the vertical part the model is a smoothed mix between the Vestøl model used in the Fennoscandia area, and the Lambeck model (Lambeck et al. 1998 a and b) used in the Baltic and northern central European area. While the model by Vestøl is a pure empirical model (based on observations at mareographs, from repeated levellings, and from permanent GPS stations), the Lambeck model is a geophysical GIA prediction model however with no modern evidence from GNSS included. As an additional tuning advocated by the NKG Working Group, the mixed model rely very much on repeated precise levelling especially in areas remote from the tide gauges or permanent GPS sites. The weakness of such a model lies clearly in a possible overestimation of the robustness of precise levelling where the network is sparse. We have confined ourselves to using this model on operational grounds. This does not necessarily reflect an agreement as to using the currently best possible model. However, a future revision would have to be based on an in-depth test of different models against different analysis strategies, which appears to be the task of a basic research project like BIFROST.

Below in Figure 5 we therefore repeated the analysis presented in Figure 4, now using the GIA prediction model of Milne et al. (2001) also for the vertical component.

In Figure **4A** and **5A** we show the differences between NKG_RF03 (in ETRS89 with internal epoch 2000.0) and the national ETR89 realisations, computed using the different internal deformation models for the vertical component, NKG2005LU(ABS) and Milne et al. (2001) respectively. We see small differences between **4A** and **5A**. In the horizontal components the statistics should be identical, and we do find negligible differences. In the vertical the differences between **4A** and **5A** are small, where the statistics are actually slightly in favour of **5A**.




```
Statistics of residuals        B) RMS  Dk:  1.8   1.4   0.9     C) RMS  Dk: 2.5   2.0   1.8
(n,e,u) and (mm)                       Fi:  1.7   1.5   5.0             Fi: 1.3   1.4   2.7
A) Mean: -3.4   10.0   24.2            No:  3.3   3.8  12.3             No: 2.6   4.1   7.5
   RMS :  6.5   14.1   27.1            Se:  1.7   1.3   3.9             Se: 1.6   1.3   3.3
```

Figure 5. *Comparison between NKG_RF03 in ETRS89 and national realisations of ETRS89 when the GIA-model of Milne et al (2001) has been used also for the vertical component; (A) NKG_RF03 reduced to internal epoch 2000.0, (B) NKG_RF03 reduced to internal epoch of each national ETRS89 realisation and national 7-parameter fit, (C) NKG_RF03 reduced to internal epoch 2000.0 and national 7-parameter fit; see text.*

The differences between **4B** and **5B** are still small but slightly more pronounced, especially in Finland and in Norway. The GIA prediction model used in Figure 5 are based on GPS observations in Sweden and Finland up to May 2000 (Johansson et al., 2002) Therefore, the differences may be attributed to incompleteness in the GIA model due to lack of GPS-station velocities from Norway, and to short GPS time series from Finland. The use of an updated GIA model may overcome these limitations (e.g. Lidberg et al 2006b).

Comparing Figure **4C** and **5C**, where the NKG_RF2003 have been reduced to a common epoch 2000.0 for all countries before transformation, we see no considerable differences between using the two models.

Studying all the four alternatives (Figure 4B, 4C, 5B, and 5C) for transforming NKG_RF03 to the national ETRS89 realisations, we may actually conclude that the use of the geophysical meaningful GIA prediction model and a common epoch for internal deformation (2000.0) in Figure **5C** would in statistical measures be as good as any other alternative.

6. NKG_RF03 for use in evaluation of geoid determination

In geoid determination, e.g. while computing a common Nordic or even a European geoid model, the achieved model are commonly evaluated by comparing geoid heights from the model (*N*) with "GPS minus levelling" (*h-H*) for some control stations. For this comparison to be principally valid, the height above the ellipsoid (*h*) of the GNSS-derived 3D positions must be internally consistent. The reference frame used for the 3D positions, for the levelled heights, and for the geoid model must also be compatible.

Thanks to the recent development in gravimetric geoid determination, the potential accuracy of geoid modelling has increased considerably (Ågren et al. 2006b). Residuals at the 1 cm level from the fit between a computed (quasi-)geoid and GPS-levelling are shown for Sweden. (Because the model by Ågren et al. (2006b) only covers Sweden, we used the NKG2004 geoid model by Forsberg et al. (2004), which covers the complete Nordic area, in the comparisons below.)

Studying the vertical component of the residuals in Figure **4A**, where NKG_RF03 (in ETRS89, internal epoch 2000) is compared to the different national ETRS89 realisations, we observe a large bias at the 25 mm level, but also variations in these residuals (from -15 mm in Poland to +45 mm in Finland). As discussed in Section 4, we assign these differences to primarily discrepancies in reference frame realisations and due to different epochs of internal deformation due to GIA in the national ETRS89 realisations.

From the residual plots in Figure **4A** and **5A** above it may be concluded that the "mosaic" of official national ETRS89 realisations may not fulfil the requirements from geoid modelling as a homogenous reference frame at the 1 cm level. Therefore we suggest that NKG_RF03 may be used in these kinds of applications instead.

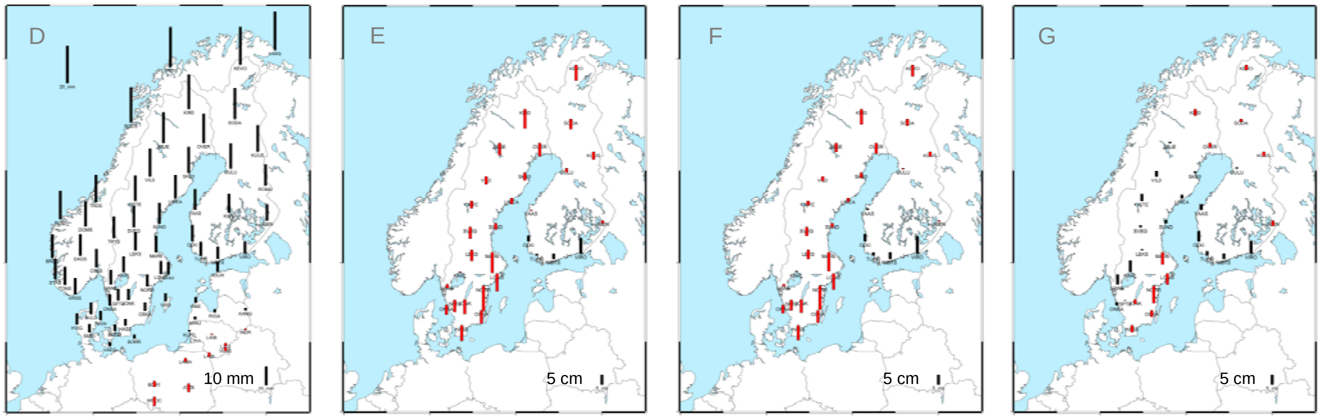


Figure 6. *Comparison between levelled heights from the Baltic Levellig Ring (BLR) and height above the ellipsoid from NKG_RF03 using the NKG2004 geoid model. Different ways of using NKG_RF03 have been tested, see text.*

Table 2. *Statistics of the comparison shown in figure 6 (see text).*

Residual map shown in		Mean (cm)	RMS (cm)
Figure 6E	(H+N – (NKG_RF03 in ITRF2000, ep 2000.0)	4.1	5.9
Figure 6F	(H+N – (NKG_RF03 in ETRS89, ep 2000.0)	3.0	5.1
Figure 6G	(NKG_RF03, ep 2000.0 transformed to H+N)	-	3.7

In Figure 6 we have compared vertical positions from NKG_RF03 with levelled heights from the result of the adjustment of the Baltic Levelling Ring (BLR), computed as a regional realisation of EVRS (Ågren et al. 2006c).

To use NKG_RF03 for evaluation of levelling + geoid (H+N), it is essential that NKG_RF03 is reduced to internal deformation epoch equal to the levelling, i.e. year 2000.0 in our case. This can be done by reducing NKG_RF03 to ITRF2000, epoch 2000.0. However, we have here again used NKG_RF03 translated to ETRS89 with internal deformation epoch 2000.0.

Figure **6D** shows differences in the vertical components of NKG_RF03, epoch 2000.0, between when it is kept in the ITRF2000 reference frame and when it is transformed to the ETRS89. Note the slope of about 2.5 cm over the area. It thus appears important to distinguish between ITRF and ETRS89 for evaluation of geoid models.

We then computed differences $H+N-h$, where H are the new “Nordic heights” from the Baltic levelling ring, and N are geoid heights from NKG2004. Figure **6E** shows the differences when NKG_RF03 in ITRF2000, epoch 2000.0 is used for h.

In Figure **6F** we used h from NKG_RF03 in ETRS89, epoch 2000.0.

In Figure **6G,** NKG_RF03, epoch 2000.0, was transformed to $H+N$ using a shift and a tilt. The corresponding statistics are shown in Table 2.

Note that possible inconsistencies caused by different handling of the earth tide model in the 3D reference frame, in the height system, and in the geoid model (specifically whether the mean, non-tidal, or zero tidal concept has been employed for the permanent part) have not been considered in this limited study.

7. Reference frame management

In discussing principles for geodetic reference frame management from the perspective of a national geodetic and mapping authority (NMA), the wish to utilise the best available geodetic reference frames must be balanced by the demand to keep an already implemented reference frame for storage of geographic information, for construction work and for presentation purposes. This is due to the high costs incurred by a change of geodetic reference frames. For example for Sweden (~400 000 km^2, ~9 million. people, and 290 local authorities responsible for the geodetic infrastructure on the regional level) these costs have been estimated at about 16.5 M€ for the horizontal part and about 12.5 M€ for the heights (Engberg 2001).

For a successful long term maintenance of geodetic reference frames in the Nordic countries, all geodetic information must be time-tagged (Mäkinen et al 2003). This is especially important in the perspective of the on-going transition of surveying practice. Traditionally, high precision geodetic measurements have been connected to some near-by geodetic monuments in the user network, but due to the introduction of Network-RTK services these connections are made to permanent GNSS stations some 50 km away. It may also be noted that the geodetic monuments that define the national geodetic reference networks traditionally have had a spacing of some 10 km, while the spacing between stations for a national ETRS89 realisation may be several 100 km. Therefore, crustal deformations will have to be accounted for already in the near future. (For “gravity related heights” or “leveled heights”, the reference frames are still defined through the levelling bench marks and are therefore not included in this discussion.)

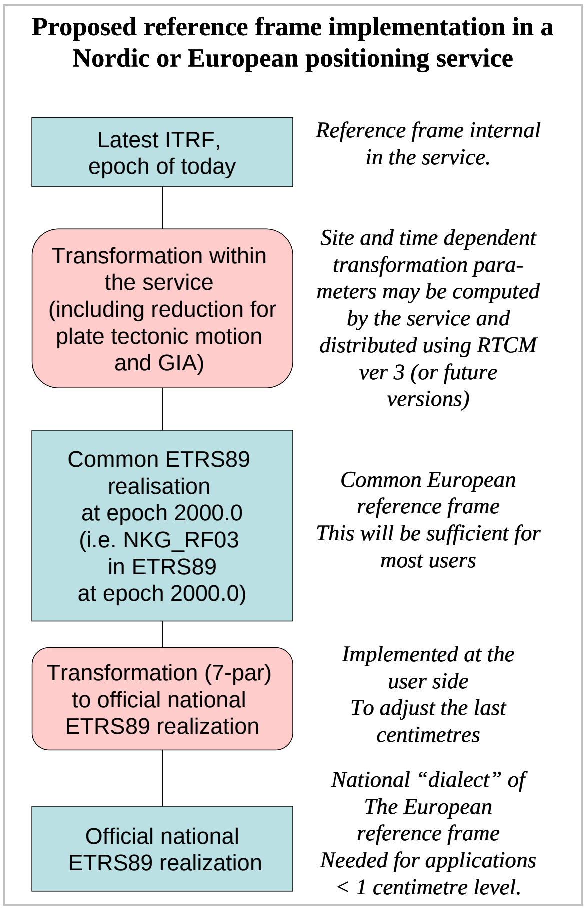


Figure 7. *Schematic description of proposed reference frame implementation.*

In connection with the transition of surveying practice, the geodetic reference frame is made available to the users through positioning services, which may be real-time (network-RTK-) services, or automated post-positioning services (Jivall et al. 2000). A possible implementation of a reference frame strategy in this context is visualised in Figure 7. We assume that future high-precision positioning services must utilise the best available reference frame internally, i.e. the latest ITRF in epoch of “today”. However, the user will need the result in ETRS89, possibly according to regulations from the European Union. For highest accuracy demands, ETRS89 is obviously what is consistent with the official national ETRS89 realisations (dedicated scientific applications are left out of the discussion for the moment). To achieve this, the deformations caused by the Fennoscandian GIA process must be accounted for. For less accurate applications (e.g. possible Nordic real-time sub-decimetre services, or possibly a decimetre positioning service from Galileo), the few-centimetre sized discrepancies between national ETRS89 realisations are irrelevant. Potential users of these kinds of services assume that ETRS89 is sufficiently well defined for their needs.

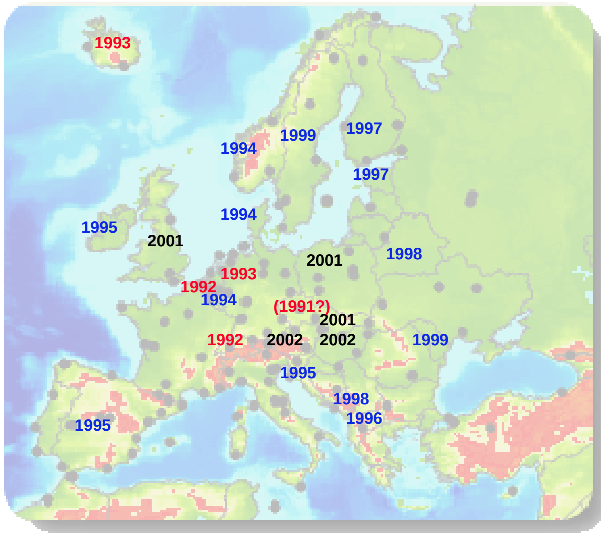


Figure 8. *Epoch of adopted ETRS89 realisations (from http://www.euref-iag.net/html/GPS-Campaigns.html). For Poland, 1992 may be a more appropriate epoch (see Section 4 above).*

In the view of national mapping authorities, it is essential that the reference frame is stable over time. Following the discussion above, the official ETRS89 implementations are the realisations based on (usually national) ETRS89 campaigns and adopted by the EUREF TWG as extensions to the realisation of ETR89. In the view of reference frame management it is important that the adopted ETRS89 realisations (Figure 8) and possible future ETRS89 realisations that follow the regulations about ETRS89 strictly, converge.

Considering also the importance of agreement with EVRS (the European Vertical Reference System), the intra-plate deformation epoch 2000.0 is a good choice. This would be beneficial for the Fennoscandian GIA area, and in the view of the consistency of coordinates, the choice would not decrease the consistency between the currently adopted ETRS89 realisations in other parts of Europe. Also the impact of a thus modified definition of ETRS89, when the typical 1 cm level of agreement between different realisations is taken into account, appears to be negligible.

8. Summary and outlook

Based on comparisons of the adopted national ETRS89 realisations in the Nordic-Baltic area and the NKG_RF03 (based on the EUREF-NKG-2003 GPS campaign), we find excellent agreement with the internal geometry (few millimetre horizontally) of the existing ETRS89 realisations when the intraplate deformations caused by the Fennoscandian GIA-process are taken into account. The agreement between the national ETRS89 realisations is at the 1cm level horizontally and slightly worse in the vertical.

A model for intraplate deformations, NKG_RF03vel developed within the NKG cooperation, has been used for accounting the Fennoscandia GIA process. It is able to represent about 90% of the observed deformations. The NKG_RF03vel model will soon be made publicly available, and therefore will be possible to use in coordinate transformations by everyone. This model should be considered as a first attempt to account for European intra-plate deformations and should be exposed to continuous improvements. A more complete velocity field and possibly a model for intraplate deformations covering complete Europe is the target for the EUREF project Dense European Velocity Field (DEVF) (Altamimi 2003). The main objective of the DEVF is the long term maintenance of the ETRS89.

We have also presented a strategy for reference frame management where the intraplate deformations are accounted for. This strategy is based on the firm conviction that it is necessary to have a static well defined reference frame where the coordinates are stable in time to fulfil the needs from the national mapping authorities (NMA) and from the GIS community (this situation may eventually change but will most likely remain for some decades).

To assure the investments in those countries that have obeyed the recommendations from EUREF and Inspire (2002) and adopted the ETRS89 as their national reference frame, a slight clarification regarding the epoch for intraplate deformation in ETRS89 would be beneficial. To ignore the intraplate deformation in future ETRS89 realisations would imply that ETRS89 would not fulfil the requirements from NMAs and the GIS community as a stable reference frame. Because none of the so far adopted ETRS89 realisations has performed corrections for intraplate deformations, the epoch 1989.0 would not conform to the current realisations. Therefore we have proposed year 2000.0, common to the EVRS realisation in the Nordic region, as a reasonable target epoch for intraplate deformations (when applicable) for future realisations of ETRS89.

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Progress in the Determination of a Gravimetric Quasigeoid Model over Sweden

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Abstract

One alternative to the traditional remove-compute-restore procedure that has hitherto been used to compute the Nordic geoid is to use the least squares modification method with additive corrections. This technique, which has been developed at the Royal Institute of Technology (KTH) in Stockholm, includes the least squares kernel modification together with topographic, downward continuation, atmospheric and ellipsoidal corrections.

This paper presents the most recent results from an on-going joint project between KTH and Lantmäteriet (National Land Survey of Sweden), whose main purpose is to evaluate the KTH approach numerically and to compute a gravimetric quasigeoid model for Sweden. The work should also be viewed as being conducted under the umbrella of the working group for geoid determination of the Nordic Geodetic Commission (NKG). The evaluation is made using 108 high quality GPS/levelling height anomalies covering the major parts of Sweden except for the mountainous areas to the North West. After a 4-parameter fit, the most promising attempt achieves a RMS value for the residuals of 17 mm, which should be compared to the 28 mm RMS reached by the NKG 2004 model. It is concluded that the least squares modification method with additive corrections is a promising alternative for the future.

1. Introduction

During the last 20 years a number of geoid models have been computed by the Working Group for Geoid Determination of the Nordic Geodetic Commission (NKG). The four latest models (NKG 1989, NKG 1996, NKG 2002 and NKG 2004) have all been derived using a similar technique, namely the remove-compute-restore (r-c-r) method utilising the Fast Fourier Transform (FFT) to speed up the calculations; see e.g. Forsberg (1999) and Forsberg et al. (2004). The r-c-r method implies that the surface gravity anomaly is first reduced both for the long-wavelength effects of a Global Geopotential Model (GGM) and the influence of the topography. After the application of Stokes' formula, the removed effects are restored to the height anomaly. The topographic reduction is the Residual Terrain Model (RTM) method, which means that only the difference from a smooth reference surface is removed and restored (Forsberg 1997). Furthermore, for the two latest models, a Wong and Gore-like kernel modification was applied, while for the previous models, the original Stokes' kernel was utilised.

One advantage of the r-c-r method is that the numerical operations of Stokes' integration and downward continuation are made on the reduced gravity anomaly, which is smoother compared to the unreduced counterpart. This is preferable from the numerical point of view. In this way, it becomes possible to take advantage of the high-frequency information available in the Digital Elevation Model (DEM). On the other hand, as is stressed by Sjöberg and Ågren (2002) Sjöberg (2005), the r-c-r method cannot do magic and requires that the involved corrections are computed with sufficient accuracy.

The overreaching goal of the NKG Working Group for Geoid Determination is to compute a 1-cm (1 sigma) quasigeoid model for the whole Nordic area. To achieve this, it has been deemed necessary to improve the applied theory and to investigate alternative computation techniques. One such technique is the least squares modification method with additive corrections, which has been developed at the Royal institute of Technology (KTH) in Stockholm; see Sjöberg (1991), Sjöberg (2003b), Ågren (2004), and Kiamehr (2006). It includes least squares modification of Stokes' kernel and separate (additive) corrections for the effects of the topography, downward continuation, atmosphere and the ellipsoidal shape of the Earth.

The main purpose of this paper is to present the most recent results from an on-going joint project between KTH and Lantmäteriet (National Land Survey of Sweden). Important aims of the project are to evaluate the least squares modification method with additive corrections numerically and to compute a gravimetric quasigeoid model over Sweden. The project is also meant to contribute to the NKG efforts to evaluate different geoid computation methods, even though it is initially limited to Sweden. In the future the area might easily be extended to all the Nordic countries.

2. The least squares modification method with additive corrections

Several different versions of the least squares modification method and the so called additive corrections have been presented during the years; see e.g. Sjöberg (2003b). In this section only the version applied in this paper is treated, which is the technique for estimation of height anomalies that is presented in Ågren (2004).

In the least squares modification of Stokes' formula (e.g. Sjöberg 1991), Stokes' kernel is modified in such a way that the expected global mean square error is minimised. This technique can be applied with the standard remove-compute-restore estimator (e.g. Ågren 2004), but according to the KTH practice the so-called *combined estimator* is preferred (Sjöberg 2003b). This means that Stokes' formula (truncated to a cap) is applied to the uncorrected surface gravity anomaly, Δg. After that, the height anomaly ζ is computed by adding a number of corrections, i.e.

$$\zeta = \frac{R}{4\pi\gamma}\iint_{\sigma_0} S^M(\psi)\Delta g d\sigma + \frac{R}{2\gamma}\sum_{n=2}^{M}\left(s_n + Q_n^L\right)\Delta g_n^{GGM} + \delta\zeta_{COMB} + \delta\zeta_{DWC} + \delta\zeta_{ATM} + \delta\zeta_{ELL} \tag{1}$$

where σ_0 is the spherical cap, R is the mean Earth radius, γ_0 is mean normal gravity, $S^L(\psi)$ is the modified Stokes' function, s_n are the modification parameters, M is the maximum degree of the Global Geopotential Model (GGM), Q_n^L are the Molodensky truncation coefficients and Δg_n^{GGM} is the Laplace harmonic of the gravity anomaly determined by the GGM of degree n.

The four *additive corrections* are derived in such a way that the same result is ideally obtained as when the remove-compute-restore technique is utilised (except for numerical effects). They can be computed as:

- The *combined topographic effect* $\delta\zeta_{COMB}$ vanishes in the height anomaly case (e.g. Sjöberg 2000).
- The *downward continuation effect* $\delta\zeta_{DWC}$ is (Sjöberg 2003a; Ågren 2004),

$$\delta\zeta_{DWC}(P) = 3\frac{\zeta_P^0}{r_P}H_P + \frac{R}{2\pi}\sum_{n=2}^{M}\left(s_n + Q_n^M\right)\left[\left(\frac{R}{r_P}\right)^{n+2} - 1\right]\Delta g_n^{GGM}(P) + \frac{R}{4\pi\gamma}\iint_{\sigma_0} S^M(\psi)\left(\left.\frac{\partial\Delta g}{\partial r}\right|_Q\left(H_P - H_Q\right)\right)d\sigma_Q \tag{2}$$

where P is the computation point, H is the topographic height, $r_P = R + H_P$, ζ_P^0 is an approximate value of the height anomaly and Q is the running point in Stokes' integral. Notice that the downward continuation effect for the height anomaly case in Eq. (2) also includes a correction for the fact that the extended Stokes' function is not utilised in Eq. (1); see Ågren (2004, Subsect. 9.5.1)

- The *combined atmospheric effect* $\delta\zeta_{ATM}$ can be approximated to order H by (Sjöberg and Nahavandchi 2000)

$$\delta\zeta_{ATM}(P) \approx \delta N_{ATM}(P) = -\frac{2\pi R\rho_0}{\gamma}\sum_{n=2}^{M}\left(\frac{2}{n-1} - s_n - Q_n^M\right)H_n(P) - \frac{2\pi R\rho_0}{\gamma}\sum_{n=M+1}^{\infty}\left(\frac{2}{n-1} - \frac{n+2}{2n+1}Q_n^M\right)H_n(P) \tag{3}$$

where ρ_0 is the atmospheric density at sea level, H_n is the Laplace harmonic of degree n for the topographic height and M is the maximum degree of the GGM.

- The *ellipsoidal correction to the modified Stokes' formula* $\delta\zeta_{ELL}$ to order e^2 is (Sjöberg 2004):

$$\delta\zeta_{ELL} \approx \delta N_{ELL}(P) = \frac{R}{2\gamma}\sum_{n=2}^{\infty}\left(\frac{2}{n-1} - s_n^* - Q_n^M\right) \cdot \left(\frac{a-R}{R}\Delta g_n^{GGM}(P) + \frac{a}{R}\left(\delta g_e\right)_n\right) \tag{4}$$

where $s_n^* = s_n$ if $2 \le n \le M$ and $s_n^* = 0$ otherwise. Furthermore,

$$\left(\delta g_e\right)_n = \frac{e^2}{2a}\sum_{m=-n}^{n}\left\{\left[3 - (n+2)F_{nm}\right]T_{nm} - (n+1)G_{nm}T_{n-2,m} - (n+7)E_{nm}T_{n+2,m}\right\}Y_{nm}(P) \tag{5}$$

in which T_{nm} are spherical harmonic coefficients for the disturbing potential. See Sjöberg (2004) for the ellipsoidal coefficients E_{nm}, F_{nm} and G_{nm}.

If Eqs. (1) to (3) are studied, it can be seen that the method is equivalent to analytical continuation to point level using the g_1 term in Moritz (1980, Sect. 45). It differs from Moritz' method in that the least squares modification of

Stokes' formula is utilised with improved atmospheric and ellipsoidal corrections.

One problem with using the combined quasigeoid estimator in Eq. (1) is that Stokes' quadrature is made on the rough surface gravity anomaly, which results in large *discretisation errors*. However, by taking advantage of the remove-compute-restore philosophy for the gridding of a comparatively dense gravity anomaly grid using a smoothing topographic correction, such errors can be counteracted; see Ågren (2004). This makes it possible to take advantage of the high-frequency information available in the DEM. A practical drawback here is that dense grids are required in rough mountain areas, which can be cumbersome.

Some advantages with the combined estimator are that the "real" importance of the correction terms is apparent and that it is easier to compute the atmospheric and ellipsoidal corrections in this way. One also avoids the global quadrature required to compute the direct and indirect topographic effects when the remove-compute-restore estimator is used.

3. Data used to compute and evaluate the gravimetric quasigeoid

In this section the gravity and height data utilised in the computation of the Swedish quasigeoid are first described. After that, more details are given concerning the gravity anomaly gridding procedure referred to at the end of the last section. The section ends with a presentation of the GPS/levelling observations that are used for the evaluation of the computed gravimetric quasigeoid models. Notice that the data presented here are used to estimate the quasigeoid by means of the least squares modification method with additive corrections. The NKG 2004 model, to which the new results are compared in Sect. 4, was computed using similar, but not exactly the same, gravity and height data; see Forsberg et al. (2004).

Gravity anomaly data

The most important information concerning the surface gravity anomaly data is summarised in the following list:

- 495 614 gravity observations are picked out from the NKG gravity database for the area illustrated in Fig. 1.
- Multiple observations at the same location are cleaned. This step is made by computing the weighted average of all multiple observations at one location. No gross error detection has yet been implemented in this step.
- Selection of the observation with smallest standard deviation in each compartment of a grid with 2km x 2km resolution using the GRAVSOFT program SELECT (Forsberg 2003). Gravity anomalies with standard errors larger than 8 mGal are neglected. The same step was carried out for the NKG 2004 model; see Forsberg et al. (2004).

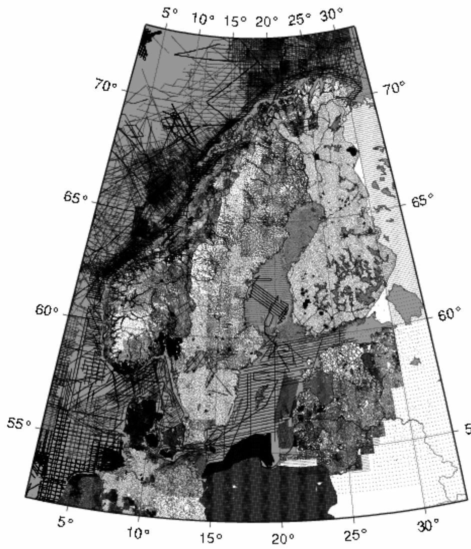

Fig. 1. *Gravity observations from the NKG database*.

Digital elevation models

Two different DEMs are used in the processing:

- The Nordic elevation model SCANDEM 2004 (Bilker 2004) is densified to 500m x 500m resolution using the Swedish photogrammetric DEM. In other areas spline interpolation is used to obtain the denser grid. It is also extended to the South using SRTM30. The result is called the *modified* SCANDEM 2004 model
- Spherical harmonic coefficients for the global topography are needed to compute the combined atmospheric correction by Eq. (3). A worldwide 15' x 15' DEM is first derived from SRTM30 and GTOPO30. Spherical harmonic coefficients are then estimated to the maximum degree 720 using numerical integration according to the midpoint rule.

Gridding of the gravity anomalies

As mentioned above, a remove-compute-restore strategy is utilised to reduce the discretisation errors. The resolution of the grid is chosen to 1' x 2'. The denser resolution 20'' x 40'' has also been tested, but the results are practically the same for the parts of Sweden covered by GPS/levelling observations; cf. below. The following gravity anomaly effects are reduced and restored:

- The long-wavelength effect from a GGM with maximum degree *M*. See Tab. 3 for the GGMs in question.
- The high-frequency part of the topographic effect computed by the RTM method with a smooth reference surface (corresponding to *M*). The TC program in GRAVSOFT (Forsberg 2003) is applied for this task.

The gridding of the reduced gravity anomalies is made in two steps:

- Search for gross errors by cross validation. Each reduced observation is predicted from its neighbours using inverse distance interpolation. If the obtained difference is larger than 20 mGal, then the observation is rejected. It might be argued that the rejection limit is too low. However, since comparatively few observations are neglected in Sweden, the limit seems suitable for the present project. At this point, no detailed investigation has been made of the observations with large cross validation residuals.
- The gridding is made by least squares collocation using individual weights for the reduced gravity anomaly observations. The GRAVSOFT program GEOGRID (Forsberg 2003) is utilised with 25 km correlation length for the 2nd order Markov covariance model chosen empirically. It should be mentioned that several different interpolation methods have been evaluated, for instance inverse distance interpolation (Bjerhammar's deterministic method, Bjerhammar 1973, p. 324), but the best results are obtained by least squares collocation with individual weights as implemented in the GEOGRID program.

GPS/levelling observations

The quasigeoid models are evaluated using 108 GPS/levelling height anomalies in the reference systems SWEREF 99 and RH 2000; the locations are illustrated on the maps of Figs. 6 and 7. The same observations have also been utilised to construct the Swedish quasigeoid (height correction) model SWEN 05LR; see Ågren and Svensson (2006a). The stations are either permanent GPS stations (SWEPOS™) or benchmarks of the third precise levelling of Sweden. In a few cases an eccentric GPS point is used very close to the benchmark.

The normal heights in the new RH 2000 system have either been determined in the RH 2000 adjustment (Ågren and Svensson 2006b) or by utilising high quality levelling connections. The coordinates of the SWEPOS stations are very well determined. In fact, they define SWEREF 99 (Jivall 2001). All other GPS heights have been derived using at least 48 hours of observations, a Dorne Margolin T antenna and processing in the Bernese software. Below the latter are referred to as SWEREF stations. The GPS/levelling observations and standard errors are summarised in Tab. 1.

Tab. 1. *The GPS/Levelling observations and their approximate standard errors.*

Data set	#	Short description	Appr. standard errors (mm) GPS height	Normal height	Height anomaly
SWEPOS	20	Permanent GPS stations whose coordinates define SWEREF 99 (Jivall 2001)	5-10	5-10	7-14
SWEREF	88	Determined relative to SWEPOS using 48 hours of obs, DM T antennas and the Bernese software	10-20	5-10	11-22

4. Test of the gravity anomaly weighting and cap radius

Before computing the Swedish quasigeoid, a number of investigations are made of different processing options. In this and the next section the most important of these are presented. In all investigations the quasigeoid determination scheme outlined in Sect. 2 is applied, utilising all the additive corrections together with the least squares modification of Stokes' formula.

When applying the least squares modification method it is important to apply realistic weights to the GGM and the terrestrial gravity anomalies. Another important choice is to determine the spherical radius of the integration cap σ_0. In this section, the influence of these options is studied numerically for the Swedish case.

Three different weighting strategies were tested: low, medium and high weighting of the gravity anomalies. In all cases, the error degree variances are assumed to be a combination of white noise and the reciprocal distance model (Moritz 1980, Sect. 23; see also Ågren 2004). The signal degree variances are generated according to the Tscherning and Rapp (1974) model. It should be mentioned that both the signal and error degree variances are rescaled to fit the regional (Swedish) situation as good as possible.

The gravity anomaly weightings are characterised by the spherical harmonic degree *K*, for which the error degree variance of the GGM is equal to that of the terrestrial gravity anomaly; see the illustration in Fig. 2. For lower degrees the GGM is more accurate and vice versa. This characterisation is preferred since it has been found numerically that the choice of *K* is crucial for the behaviour of the least squares modification (presupposing, like here, that the gravity anomaly error degree variances decrease for the degrees available in the GGM).

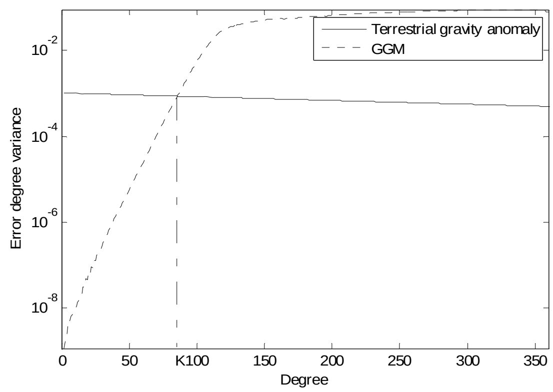

Fig. 2. *Illustration of the spherical harmonic degree K for which the error degree variances for the GGM and terrestrial gravity are equal.*

It seems realistic to choose the error degree variances in such ways that the GGM is more accurate for the lower degrees, while the terrestrial gravity becomes better and better for higher frequencies. For very high degrees, the white part of the noise makes the gravity anomaly error degree variances increase again, but this fact is not important for the choice of modification parameters. One then specifies the degree K, for which the two sources of information are comparable. In this way, the least squares estimate will take into account the fact that the quality of the gravity anomaly observations becomes worse for lower degrees (due to datum problems, systematic errors, etc.). If, for instance, a GGM derived from GRACE is utilised, the choice of K amounts to specifying the upper degree for which the GRACE GGM is believed to be better than (or as good as) the terrestrial gravity anomalies. This corresponds to the specification of an abrupt degree in the Wong and Gore modification. One advantage of the least squares modification is that the parameters are chosen so that the truncation error is low, also for comparatively small caps. This is not the case for the Wong and Gore method, which usually requires a large integration area; see Ågren (2004).

For the high, medium and low gravity anomaly weightings statistics for the GPS/levelling residuals after a 4-parameter fit are presented in Tab. 2. The results are computed for two different choices of the integration cap radius. In all cases, the Swedish quasigeoid is computed using the method summarised in Sect. 2 and the data in Sect. 3. Spline interpolation is used before Stokes' integration to densify the 1' x 2' surface anomaly grid 9 times to a 6.66'' x 13.33'' grid. The contribution from the central block is treated according to the method in Ågren (2004, Subsect. 5.2.1). The computation of the additive corrections is commented on in Sect. 6. It should further be mentioned that the GGM is constructed using GGM02C (Tapley et al. 2005) up to degree 200. Above that, up to degree 360, the EGM 96 coefficients (Lemoine et al. 1998) are utilised. The model is very similar to the GGM used for the Nordic model NKG 2004.

Tab. 2. *Evaluation of different weighting schemes and integration radii. Statistics for the 108 GPS/ levelling residuals after a 4- parameter fit. GGM02C /EGM 96. Unit: mm.*

Δg weight	K	ψ_0 (deg.)	Min	Max	Mean	StdDev
High	65	3.0	-42	51	0	17
Medium	85	3.0	-38	56	0	16
Low	105	3.0	-45	46	0	22
Medium	85	2.0	-38	43	0	17

Considering the standard errors for the GPS/levelling height anomalies in Tab. 1, it is clear that the results in Tab. 2 are very promising. The lowest residuals are obtained for the 3 degrees cap radius and the medium weighting scheme, but the results are almost as good for the high weighting and the smaller cap radius. It seems significant, however, that the low weighting scheme, which relies on the GRACE model to comparatively high degrees, yields worse results compared to the other weightings. It is concluded that GGM02C is sufficiently accurate approximately up to degree 85, but not higher. Based on the above results, the medium weighting scheme (K = 85) and the cap radius $\psi_0 = 3°$ are assumed in all computations presented below.

5. Evaluation of three GGMs originating from GRACE

In this section three different GGMs are tested, which are all derived from GRACE. It should be emphasised that the GGMs are tested with the full quasigeoid determination method of Sect. 2, using all the additive corrections and the least squares modification of Stokes' formula. The first GGM is the combined GGM02C/ EGM 96 introduced in the last section, which is complete up to degree 360. The second is the combined EIGEN GL04C (http://www.gfz-potsdam.de/ pb1/op/grace/results/) using the same maximum degree. Since both these models contain high-frequency information stemming from more or less the same gravity anomalies as are used in the least squares modification, it might be argued that a satellite-only model should be preferred. One problem with a combined model is that correlations arise between the errors in the GGM and the terrestrial gravity anomalies, which are not considered in the present version of the least squares modification technique; see Sjöberg (1991) and Ågren (2004). To find out what type of GGM that should be preferred, the satellite-only model GGM02S (Tapley et al. 2005) up to the degree 110 is also tested. Statistics for the GPS/levelling residuals after a 4-parameter transformation are presented in Tab. 3 below.

Tab. 3: *Comparison of using different GGMs. Statistics for the 108 GPS/levelling residuals after a 4 parameter fit. Medium gravity anomaly weighting. Unit: mm.*

GGM	M	Min	Max	Mean	StdDev
GGM02C/EGM 96	360	-38	56	0	16
EIGEN GL04C	360	-44	53	0	17
GGM02S	110	-41	52	0	20

As can be seen, the best results are obtained for the GGM02C/EGM 96 model, which is therefore chosen for the computation of the quasigeoid model over Sweden. Another conclusion is that one actually gains by using the combined model to the degree 360 compared to using the satellite-only part.

6. Magnitude of the additive corrections

The purpose of this section is to study the additive corrections for the final quasigeoid model. As mentioned in Sect. 2, one advantage of the present method is that the "real" magnitude of the corrections becomes apparent, i.e. the additive corrections are equal to the quasigeoid errors obtained in case no corrections are applied at all.

The downward continuation correction

This correction is computed according to Eq. (2) using the chosen combined GGM (GGM02C/EGM96) with $M = 360$. The topographic heights for the computation point P and the running point Q are interpolated using the bilinear method from the *modified* SCANDEM 2004; see Sect. 3. The downward continuation to point level (Moritz 1980; Sect. 45) is approximated using the vertical gradient of the gravity anomaly. This quantity is calculated by the standard formula Eq. (2-217) in Heiskanen and Moritz (1967) using the surface gravity anomaly grid; see Sect. 3. The magnitude of the downward continuation correction is illustrated in Fig. 3.

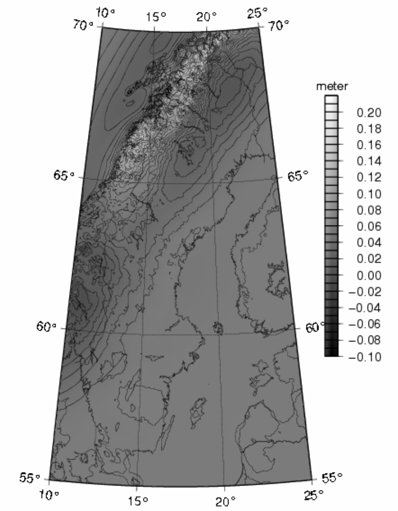

Fig. 3. *The downward continuation correction* $\delta\zeta_{DWC}$. *1 cm contour interval.*

It is clear that the downward continuation correction is large in, and close to, the mountainous areas in the Northern and Western parts of Sweden. In the lowlands, however, the correction is small; at the 1-cm level. Another observation that can be made in Fig. 3, is that the high-frequency details are small, usually below 1 cm. It is concluded that it is important to take the correction into account. It should be pointed out that the correction has been computed using the first-order approximation; cf. Moritz (1980, Sect. 45). It is believed that this approximation is sufficient in the region. In any case, as is shown by the synthetic model investigations in Ågren (2004), it is extremely difficult to perform the downward continuation more strictly in practice, using for instance the inversion of Poisson's integral.

The combined atmospheric correction

This correction is computed using Eq. (3) from the spherical harmonic expansion of the global topographic elevation truncated to the maximum degree 720; see Sect. 3. The maximum degree of the GGM is still $M = 360$. The correction is illustrated in Fig. 4.

The most important thing to notice in Fig. 4 is that the combined atmospheric correction is barely significant. It should be noticed, though, that the correction depends on the kernel modification. It is, for instance, considerably larger for the original Stokes' kernel (Ellmann 2004). It also depends on the cap radius and maximum degree of the GGM. This means that the computation of the correction is not meaningless. Its magnitude should be checked whenever a new modification, cap size or maximum degree of the GGM is applied.

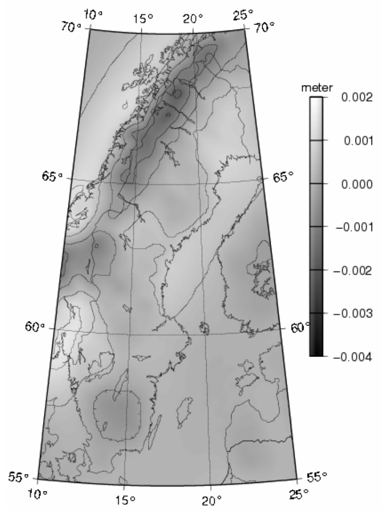

Fig. 4. *The combined atmospheric correction* $\delta\zeta_{ATM}$. *1 mm contour interval.*

The ellipsoidal correction

The ellipsoidal correction to the modified Stokes' formula is computed according to Eqs. (4) and (5) using the selected GGM02C/EGM 96 model with maximum degree $M = 360$. The result is given in Fig. 5.

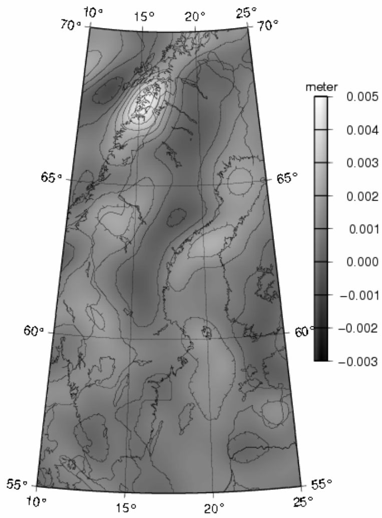

Fig. 5. *The ellipsoidal correction* $\delta\zeta_{ELL}$. *1 mm contour interval.*

The ellipsoidal correction is a little bit larger compared to the atmospheric counterpart in Fig. 4, but it is still small, well below the 1 cm level.

Both the atmospheric and ellipsoidal corrections are thus small for the chosen version and parameters of the least squares modification method. It should be emphasised, though, that the above additive corrections depend on the modification method, cap size and maximum degree of the GGM being used. Consequently, one should not jump to conclusions concerning their *general* importance based on the *particular* results presented in this section.

7. Analysis of the new model and comparison with NKG 2004

The new quasigeoid model for Sweden is computed using the above theory, data and parameter choices. In what follows it is referred to as the LSMM (Least Squares Modification Method) model. In this section the corresponding GPS/levelling residuals are studied more carefully and a comparison is made with the best quasigeoid model previously available, namely the Nordic NKG 2004 model introduced in Sect. 1.

The residuals after a 4-parameter fit of the LSMM model are plotted in Fig. 6. The corresponding statistics are given in Tab. 4 below. Notice that the same information also occurs in Tabs. 2 and 3. (Remember that the tests of processing options and of GGMs presented in the latter tables were made using the full quasigeoid determination technique presented in Sect. 2.)

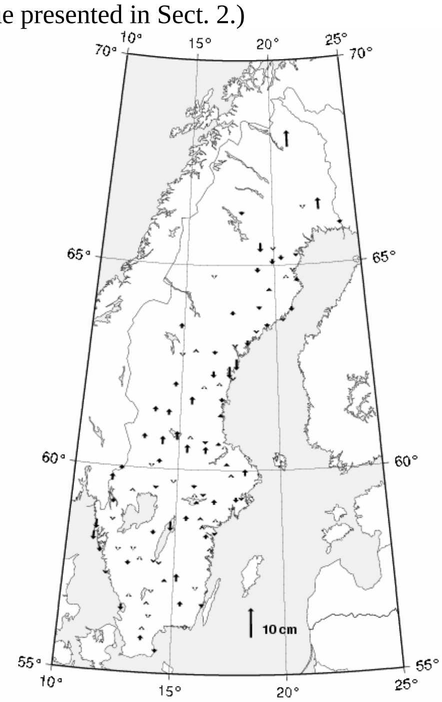

Fig. 6. *GPS/levelling residuals for the LSMM model. The scale is given by the 10 cm arrow to the South-East.*

As can be seen in Fig. 6, the fit to the GPS/levelling is good and homogeneous for the whole area covered by GPS/levelling observations. One problematic residual is the SWEPOS station in Kiruna, which is the northernmost arrow in Fig. 4. Another problem is that there seem to be a systematic bulge in the central part of the country. However, if the estimated standard errors of the GPS/levelling (Tab. 1) are considered, then the main conclusion is that the results are very good. For instance, if the standard errors for GPS and levelling are taken as 10 mm and 5 mm, respectively (which is quite optimistic), then the propagated standard error for the fitted gravimetric quasigeoid becomes 11 mm. It should be pointed out, though, that no GPS/levelling observations are yet available in the Swedish mountains to the North-West. Hence, when these observations are extended to the whole country, then it is expected that the results will deteriorate significantly.

Tab. 4. *Comparison of the LSMM (medium weighting of* Δg *, GGM02C/EGM96) with NKG 2004. Statistics for the 108 GPS/levelling residuals after a 4 parameter fit. Unit: mm.*

Geoid model	Min	Max	Mean	StdDev
LSMM	-38	56	0	16
NKG 2004	-70	88	0	28

Next, the LSMM model is compared to the NKG 2004 counterpart. As discussed in the introduction (Sect. 1), NKG 2004 was computed by the remove-compute-restore method using the RTM reduction and a Wong and Gore type of modification, selected to high pass filter the gravity anomalies above the degree 30. The NKG 2004 model is documented in Forsberg et al. (2004). It should be pointed out, however, that this documentation is of a preliminary version of NKG 2004. The final model was computed in almost the same way, the largest difference being that the brand new GRACE model GGM02S/C (Tapley et al. 2005) was applied.

It should be pointed out that the NKG 2004 and LSMM models have not been computed using exactly the same data. Of course, this implies that the comparison cannot be absolutely conclusive with respect to the computation method. However, it is still the case that almost the same observations are applied. Approximately the same GGM are utilised in both cases (GGM02C/S and EGM 96 for the highest degrees to $M = 360$). The same gravity data from the NKG database are also used (at least for the overlapping area). The difference here is that the data have been handled in different ways. The applied DEMs also differ somewhat, since a denser DEM is used over Sweden for the LSMM model; see Sect. 3.

The 4-parameter fit residuals for NKG 2004 at exactly the same GPS/levelling stations (see Tab. 1) are illustrated in Fig. 7. The corresponding statistics can be found in Tab. 4. It seems clear that the NKG 2004 model is significantly worse compared to the LSMM model. Since the residuals are so small for the LSMM model, it seems highly likely that the main part of the NKG 2004 errors is located in the quasigeoid model and not in GPS and/or levelling.

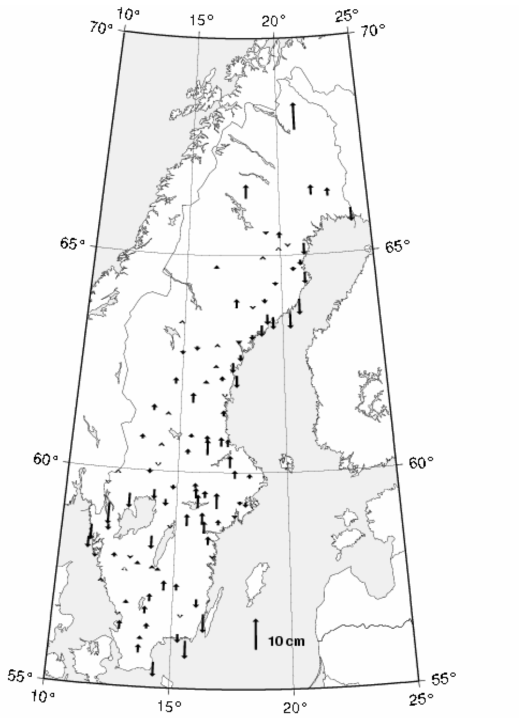

Fig. 7. *GPS/levelling residuals for the NKG 2004 model. The scale is given by the 10 cm arrow to the South-East.*

It can be further seen that the main difference between the two models is that the long-wavelength errors are larger for NKG 2004. Most likely, they are caused by various systematic errors among the gravity anomalies. Since the LSMM model makes use of the GRACE model up to degree 85, which is significantly higher than for NKG 2004 modification (degree 30), it becomes possible to high-pass filter the gravity anomalies more efficiently. However, the computation methods differ in many ways, which makes it difficult to say exactly which differences that cause the largest improvements.

8. Summary

The main purpose of this paper has been to present a number of new results from a Swedish project that aims at evaluating the methods developed at KTH numerically and to compute a new, better quasigeoid model for Sweden. The project is a joint undertaking between KTH and Lantmäteriet (National Land Survey of Sweden). It is also the purpose of the project to contribute to the work of the NKG to evaluate different geoid determination methods and theories, even though the quasigeoid has only been studied over Sweden.

After summarising the applied version of the least squares modification method with additive corrections in Sect. 2, the applied data has been described in Sect. 3. In the next two sections, some important processing options have been investigated. First, the choice of integration cap radius and gravity anomaly weighting have been studied. It is concluded that the cap radius $\psi_0 = 3°$ and the medium gravity anomaly weighing scheme (K = 85) yield the best fit to GPS/levelling. Next, three different GGM models, all derived from GRACE, have been tested. It is found that the combined model GGM02C/ EGM 96 gives the best results. Based on these results, it was decided to use the medium weighting scheme, the cap radius $\psi_0 = 3°$ and the GGM02C/ EGM 96 model for the new quasigeoid model over Sweden.

The magnitudes of the additive corrections have been investigated in Sect. 5. The main result is that atmospheric and ellipsoidal corrections are very small for the present modification, integration radius and maximum degree M. The downward continuation correction is much larger.

In Sect. 6, the computed quasigeoid model (the LSMM model) has first been evaluated more carefully. After that, the LSMM model has been compared to the best model so far available for Sweden, namely the Nordic NKG 2004 model. The 16 mm standard error obtained in the fit is promising. If the standard errors for GPS and levelling are taken as 10 mm and 5 mm, respectively (which is quite optimistic), then the propagated standard error for the fitted gravimetric quasigeoid becomes 11 mm. However, it should be noticed that the GPS/levelling observations are located in the comparatively flat areas of the country. In the near future, they will be extended also to the mountainous parts to the North West, which will provide a tougher test.

The results are significantly better for the present method compared to the technique used NKG 2004. It is believed that the main improvement is due to the reduction of the long-wavelength errors; cf. for instance the systematic bulges south of the 60° latitude. It is believed that a large part of these errors is due to systematic errors in the terrestrial gravity. By utilising the GRACE derived GGM up to higher degrees, it becomes possible to high-pass filter the gravity anomalies more efficiently.

Acknowledgements

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On the Construction of the Swedish Height Correction Model SWEN 05 LR

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The height correction model SWEN 05 LR was released in connection with the new Swedish height system RH 2000. It is used to relate normal heights in this system to GPS heights above the ellipsoid in SWEREF 99. The main purpose of this poster is to describe how SWEN 05 LR was constructed by the National Land Survey and to evaluate its accuracy numerically in different parts of Sweden.

SWEN 05 LR is derived by first fitting the gravimetric geoid model NKG 2004 to 1178 GPS/levelling observations covering the main (inhabited) parts of the country by means of a 1-parameter transformation (a shift). Corrections for the land uplift and different treatments of the permanent tide are also applied. After that, the residuals are modelled by least squares collocation with different weights for the GPS/levelling observations, the apriori standard errors being chosen depending on the quality of the GPS height in question. It is concluded that the standard error of SWEN 05 LR is somewhere around 15 mm in those areas where GPS/levelling observations are available and approximately 40 mm otherwise, even though larger errors might be expected in the highest mountains.

GRAVIMETRIC QUASIGEOID IN SOUTHERN BALTIC

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Altimetry-derived, sea-borne, airborne and terrestrial gravity anomalies as well as terrain elevation data were used for generating a precise quasigeoid model in southern Baltic. All data used were analysed and verified. The long-wavelength component of height anomaly was derived from GGM02S/EGM96 global geopotential model. The short-wavelength component was calculated using SRTM3 terrain model. Two methodologies were used in modelling of medium-wavelength part of height anomaly: the FFT with modified Wong-Gore kernel modification and the least squares collocation, both with weighting of residual gravity data. The results of different modelling methods were mutually compared; they were also compared with existing gravimetric and GPS/levelling quasigeoid models. The comparisons became the basis to estimate optimum kernel modification level and to choose the best quasigeoid model.

Comparison of the Gravimetric geoid NKG04 against the geoid surface tracked by GPS on some areas of the Baltic Sea

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Abstact

This paper compares the gravimetric geoid NKG04 (Forsberg, Stykovsky, Bilker, 2004) for some areas of the Baltic Sea with the level surface detected by GPS measurements on the sea. The geoid of the Nordic Countries (NKG04, developed by KMS) is computed from the gravimetric data. On the earth surface we can compare the gravimetric geoid with GPS-levelling to get accuracy estimation and tilt information. On the sea we can do it using the GPS methodology and eliminating the present water tilt corrections and the effect of sea surface topography. The existent GPS device on board a ship stores data every second and determines the heights with an accuracy of a few centimetres (using the kinematic method with post-processing, several base stations close to the ferry line). As a result, it is possible to observe the present relative water level profile in reference to the ellipsoid. If we take into account the tilt of the water level at the moment of measurement, we can observe the relative change of the geoid using independent methodology, which serves as a comparison to the gravimetric geoid solution.

With this method we explored some areas on the Baltic Sea covered with regular ferry lines where the geoid profile changes faster. One such area lies about 30 km north of the island of Hiiumaa, where the geoid has a "lump": the separation of the geoid from the ellipsoid changes by 1 meter over a 70-km distance starting from Paldiski; further towards Sweden the original separation is restored. In addition, we analyzed all the Estonian and Swedish profiles, also using GPS data from Swedish base stations.

We also performed the same kind of measurements on ferries running the regular line Tallinn-St. Petersburg-Helsinki-Tallinn. Those measurements were of particular interest as there was no gravimetric data available for the eastern part of the Gulf of Finland (Jürgenson, 2003).

As a third track, measurements were performed on liners running between Sillamäe and Kotka.

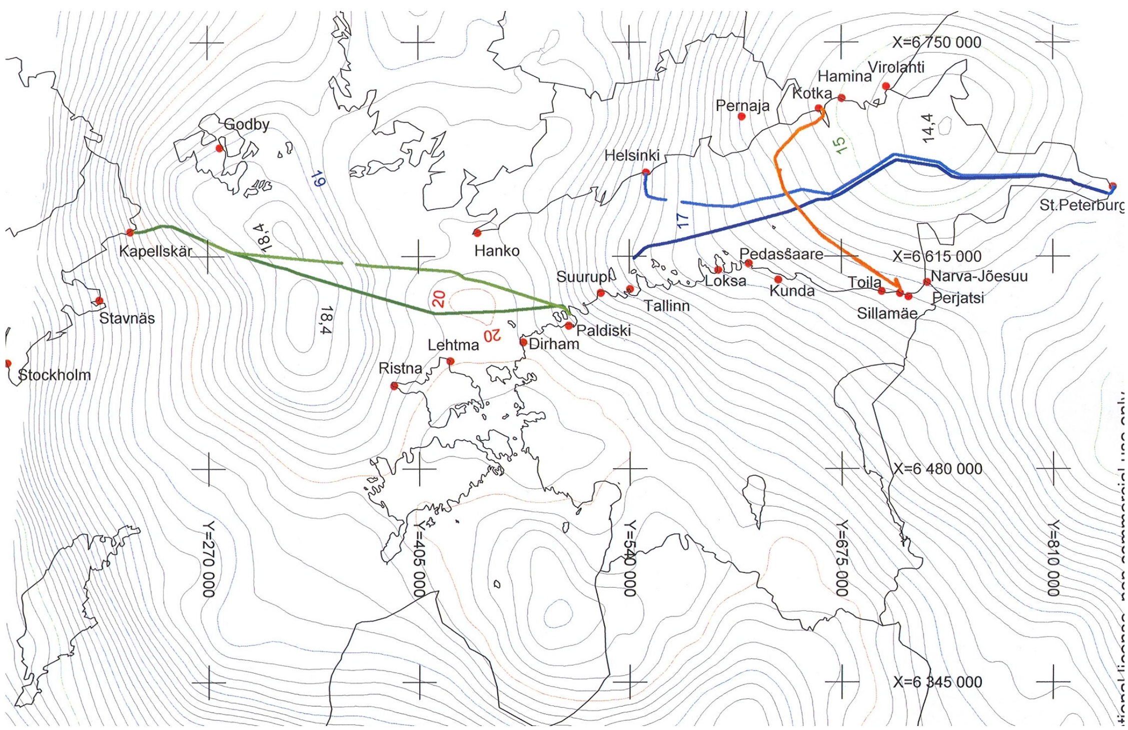

Fig. 1. *Tracks measured by GPS on ferry. Background is Geoid Model NKG04; contour interval is 0.2 m (500,000 m responses to longitude 24°).*

The results show that the 150-km geoid NKG04 profile close to Hiiumaa did not differ any more than 15 cm from the GPS-measured level surface. The influence of the water tilt was more or less eliminated using the available tide gauge data. The profile between Tallinn and St. Petersburg manifested similar difference. Most of the measurements were repeated several times on the same profile.

Introduction

The gravimetric geoid NKG04 was derived by KMS using all the gravimetric data available from the region. Unfortunately, the data set does not originate from one and the same time period, the coverage is not homogeneous, and the quality varies from region to region. Some areas, including those close to Estonia, such as the eastern part of the Gulf of Finland, are almost uncovered by gravity measurements. The Baltic Sea was measured by airborne gravimetry with the accuracy of probably 2 mGal. Our idea was to compare the geoid for the sea areas with an independent method. We used GPS-measurements and ferries on regular lines to cover areas on the Baltic Sea. The good coverage of the GPS permanent base stations made the measurements easier. How to eliminate water tilt during the campaign was the main hurdle to negotiate.

Method

A GPS receiver was placed on a ferry, using kinematic technology (or real-time kinematic). The GPS receiver stores the position and the height every second. Post-processing was performed using several base stations located close to the measured line. The GPS receiver was placed on the open deck of the ferry (Fig. 2) and was static during the measuring period. GPS receivers Trimble 5700 and 5800 were used. We only wanted to determine the relative change of the level surface; the absolute height from the sea level was not important. In some instances, two GPS receivers were used simultaneously on the ferry (Sillamäe – Kotka ferry line).

During the measurements, the present water level heights were obtained from the closest tide gauges for water tilt estimation. After processing the GPS data, the water tilt correction was added. The wave effect was eliminated using the trend line of real stored points. Estonian tide gauges provide a water level relative to the Baltic height system (BK77) and Finnish ones relative to the mean sea level. The mean sea level values of tide gauges were recalculated into the N60 height system to eliminate the land uplift effect. The formula presented by The Finnish Institute of Marine Research (http://www.fimr.fi) was used.

The Finnish N60 height system differs from the BK77 system by about 3 cm (Jürgenson, Kall, 2004). Furthermore, the Estonian height system has been affected by relative land uplift – about 6 cm during the 30 years. However, the Estonian tide gauges used in the campaign are situated often in the region with similar land uplift. Hence, all the water level heights were computed to the Baltic height system BK77 before they were used.

The mean sea topography was small in the tested regions, about 4 cm between Tallinn and St. Petersburg, (Ekman, Mäkinen, 1996) and probably 10 cm between Paldiski and Stockholm (Putanen, Kakkuri, 1999) (Fig. 3). The measuring lines were mostly shorter, as a result of which the influence was smaller and was not taken into account here.

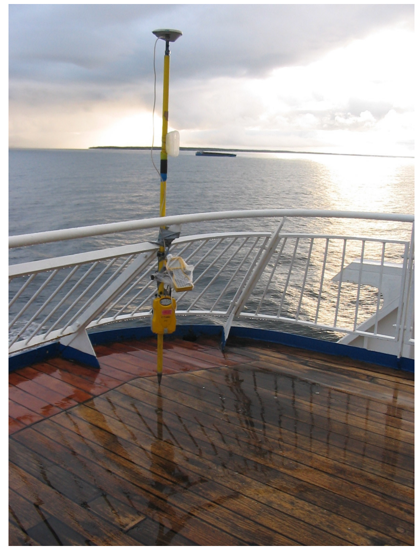

Fig. 2. *GPS Trimble 5700 on board.*

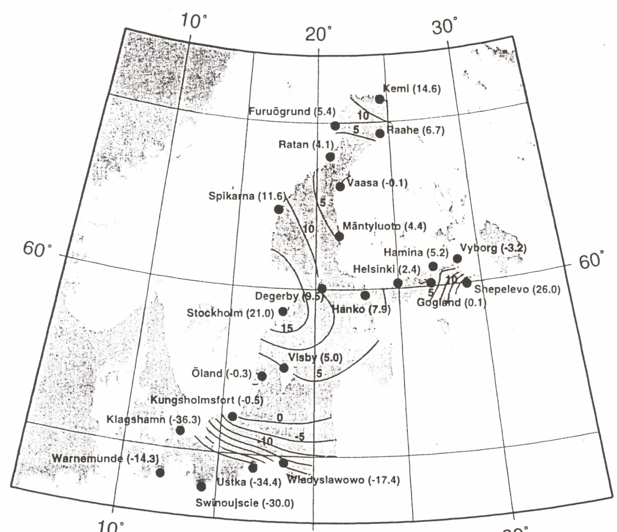

Fig. 3. *The mean sea surface topography on the Baltic Sea (Poutanen, Kakkuri 1999 a).*

The accuracy of the GPS measurements is a few cm depending on the actual atmosphere, the number of satellites and the PDOP as well as the vector length (for example 1 ppm makes 4 cm per 40 km). The number of satellites in particular may become a problem due to long distances from base stations. Planning the timing of the measurement is difficult because we are depending on the ferry schedule. Taking into account also the water tilt elimination problems, the level surface accuracy is 5-15 cm according to our estimation. Yet this method is estimation to the geoid, and actual geoid changes are usually 10 times bigger along the measuring route. This is of special interest in the case of areas for which gravimetric data is missing or has serious quality problems.

Test measurements

The first test measurements took place in 2004 between Paldiski and Kapellskäre. The method was tested in areas of faster geoid changes. One of the areas lies about 30 km to the north of the island of Hiiumaa (North-West Estonia). The area is especially interesting because the geoid surface is placed a little higher compared to the surrounding area (Fig. 4). Continuous RTK measurements were performed on board ferries running the regular line between Paldiski, Estonia, and Kapellskäre, Sweden. Two base stations were used for RTK (in Dirhami and in the north of Hiiumaa) in order to ensure that the baseline length does not exceed 34 km. A GSM connection was used for transmission of corrections. Ship speed was 30 km/h, thus the half distance (70 km) was measured during 3 hours. The westernmost part of the line was measured using the kinematic method with post-processing from the Hiiumaa base station. The storing interval of the GPS measurements was 1 and 2 seconds. Trimble 5700 GPS devices were used. The RTK fixed solution was obtained during the measurements. Wind speed was generally less than 6 km/h. The ferry's up-and-down movement was normally less than 20 cm (Fig. 5, scale of the figures is a little distorted, while only east or north component is used).

The tide gauge data did not show any remarkable changes in water level during the measurements (less than 3 cm). However, that day's water level at the tide gauges of Ristna and Dirhami (Fig. 4) differed from the mean sea level by +3 and +17 cm respectively. This indicated that water was tilted by 14 cm between the tide gauges (over 80 km in the east-west direction). The Paldiski tide gauge provided a reading similar to that of Dirhami. Unfortunately, there were no more tide gauges available in the region. From the results, a smooth trend line was generated to eliminate local sea level change caused by wind effect.

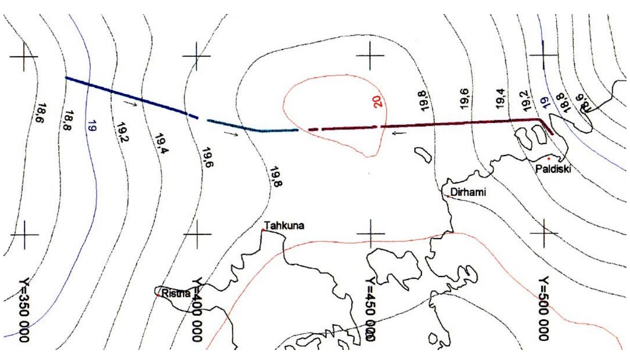

Fig. 4. *GPS measurement on ferry to determine relative geoid change. Background is the gravimetric geoid NKG04 with a contour line interval of 0.2 m.*

The gravimetric geoid difference from Paldiski to the maximum point was 92 cm (Fig. 4, 5) while the RTK GPS measurements showed a relative change of 77 cm (Fig. 5, the value was obtained from the trend line) along the same line.

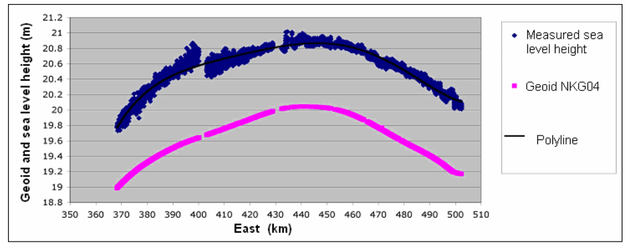

Fig. 5. *Water level relative heights by kinematic GPS between 370 and 502 km along the East coordinate (500 km responses to longitude 24°).*

If we take into account the tilt of the water level (about 7 cm per 70 km, Table 1), the results agree with about 8-cm accuracy: 92-7=85 cm, 85-77=8 cm. So, a comparison of the relative change using the gravimetric solution with the ship GPS solution showed that the preliminary results agreed within an 8-cm accuracy range for the eastern part of the test line. The middle part (measured from the Tahku base station using RTK, 410-430 km in the east-west direction) was a bit biased (ca 15 cm, Fig. 5). The last 30 km of the western part of the line were measured using kinematic measurement with post-processing.

In the western part, the water difference measured with GPS was 1.08 m. If we subtract the water tilt correction 8 cm, the water profile difference is 1 m. Similarly, the west part shows a clearly negative trend until East coordinate 370 km, as does the gravimetric geoid: by 1.1 m respectively (Fig. 5, 6). We can see that the tilt-corrected water (sea) level change agrees with the NKG04 model in the region within the range of 10 cm.

Tabel 1. *Tide gauges at Ristna, Dirhami and Paldiski.*

Station / Time	Water level BK77 (cm)
29.06.2004	
Ristna 08.00	+4
Ristna 14.00	+1
Ristna 20.00	+3
Paldiski 08.00	+17
Paldsiki 20.00	+12
Dirhami 08.00	+17
Dirhami 20.00	+14
30.06.2004	
Ristna 08.00	+3
Ristna 14.00	+5
Paldiski 08.00	+16
Paldiski 20.00	+26
Ristna 20.00	+5
Dirhami 08.00	+17
Dirhami 20.00	+23

To improve reliability the measurements were repeated on 28 and 29 June, 2004. The entire distance from Paldiski to Sweden was measured using kinematic GPS. Only the kinematic method with post-processing was used. A base station was established in the north of Hiiumaa (Lehtma, Fig. 1). Additionally, data from a second base station at Hanko was used. Fig. 6 shows the same distance as Fig. 5. Unfortunately, that time the west part of the distance was measured under a stronger wind. The water level was even more stable than the first time; the western part of the profile was about 10 cm lower; consequently, the tilt was 10 cm per 130 km (Table 2).

Table 2. *Tide gauges at Ristna, Dirhami, Paldiski and Lehtma.*

Station / Time	Water level BK77 (cm)
06.11.2004	
Ristna 08.00	-1
Ristna 14.00	-1
Ristna 20.00	+2
Lehtma 08.00	+7
Lehtma 14.00	0
Lehtma 21.00	+5
Dirhami 08.00	+7
Dirhami 20.00	+4
Paldiski 08.00	+12
Paldiski 20.00	+4
07.11.2004	
Ristna 08.00	-1
Lehtma 01.00	0
Lehtma 23.00	+8
Lehtma 07.00	+7
Dirhami 08.00	+5
Paldiski 08.00	+5

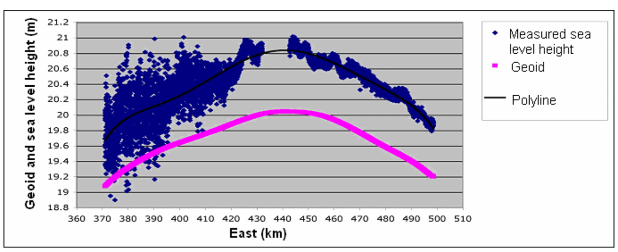

Fig. 6. *Water level relative heights by kinematic GPS over 132 km, 6 November 2004 (500 km responses to longitude 24°).*

The results are about the same as those obtained in the first round. From Paldiski to the maximum point of the gravimetric geoid the height increased by 84 cm, tilt-corrected water level 94 cm (correction applied + 4 cm) (Table 2). As well, the western part coincided within the range of 14 cm.

Measurements between Estonia and Sweden on 6 and 7 November 2004

Fig. 1 presents the measured lines between Paldiski and Kapellskäre. The aim was to measure a geoid low situated south of Marinehamn. Again, a ferry running the regular line was used; the results are presented in Fig. 7 and 8.

Additionally, data from base stations Godby and Stavsnas was used for post-processing. The stations are a part of the RTK network in Finland and Sweden respectively. As well, tide gauge data from Stockholm and Marviken was used (Table 3). All the tide gauge data were converted to the Baltic height system. As the water was almost untilted during the measurements (Table 3) we did not apply any water tilt correction. The changes in the geoid and the measured water profile coincide with each other within the range of 10 cm (Fig. 7, 8) (Morozova, 2005).

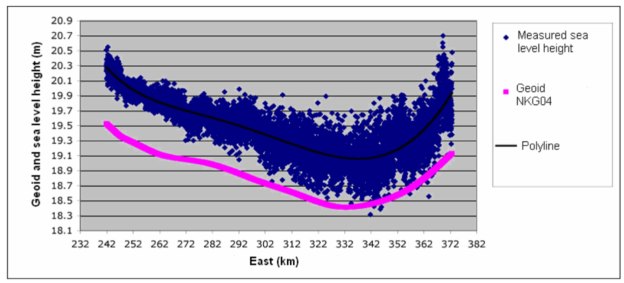

Fig. 7. *Water level relative heights by kinematic GPS, 6 November 2004 (300 km responses to longitude ~20.5°).*

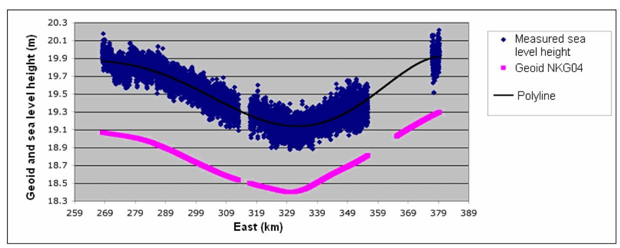

Fig. 8. *Water level relative heights by kinematic GPS, 7 November 2004 (300 km responses to longitude ~20.5°).*

Tabel 3. *Tide gauge data from some stations in Estonia and Sweden (6 and 7 November 2004)*

Station / Time	Water level BK77 (cm)
1	2
Ristna 14.00	-1
Ristna 20.00	+2
Lehtma 20.00	+5
Lehtma 23.00	+8
Stockholm 14.00	0
Stockholm 18.00	+3
Stockholm 20.00	+2
Stockholm 23.00	-1

1	2
Marviken 14.00	-5
Marviken 18.00	-3
Marviken 20.00	0
Marviken 23.00	-4
Lehtma 01.00	0
Lehtma 07.00	+7
Ristna 08.00	-1
Stockholm 23.00	-3
Stockholm 00.00	-5
Stockholm 01.00	-3
Stockholm 03.00	-8
Stockholm 05.00	-7
Stockholm 07.00	-7
Stockholm 08.00	-7
Marviken 23.00	-6
Marviken 00.00	-6
Marviken 01.00	-6
Marviken 03.00	-10
Marviken 05.00	-7
Marviken 07.00	-4
Marviken 08.00	-5

Measurements between Estonia and St. Petersburg on 13 and 14 December 2004

Fig. 1 presents the measured lines between Tallinn-St. Petersburg-Helsinki. The regular ferry was used. The results are presented in Fig. 9.

The base stations at Pedassaare and Virolahti were used for post-processing. The Virolahti base is a part of the Finnish RTK network. A dual-frequency GPS receiver Geotracer 3220 was stationed in Pedassaare (Estonian coast).

Tide gauge data from Hamina, St. Petersburg, Toila, Kunda, Loksa and Narva-Jõesuu was used (Table 4). The tide gauge data was converted to the Baltic height system. The profiles coincide within the accuracy of a few cm-s between Tallinn and St. Petersburg (Fig. 9) and about 10 cm between St. Petersburg and Helsinki.

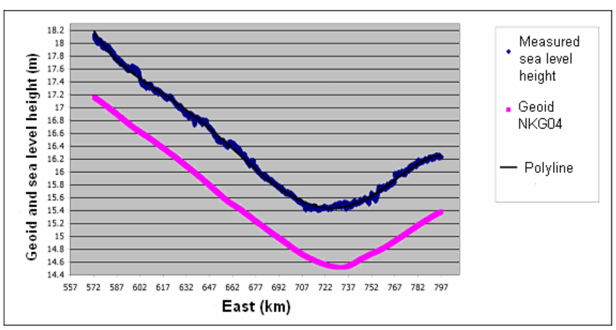

Fig. 9. *Water level relative heights by kinematic GPS between Tallinn and St. Petersburg, 13 December 2004. (700 km responses to longitude ~27.5°).*

Table 4. *Tide gauge data from some Estonian, Finnish and Russia stations (13 and 14 December 2004)*

Station / Time	Water level BK77 (cm)
Loksa 20.00	+17
Kunda 20.00	+19
Toila 20.00	+22
Narva-Jõesuu 20.00	+21
St. Peterburg 20.00	+35
Hamina 20.00	-
Helsinki 20.00	-
Hanko 20.00	-
Loksa 08.00	+21
Kunda 08.00	+21
Toila 08.00	+24
Narva-Jõesuu 08.00	+24
Narva-Jõesuu 20.00	+24
St. Peterburg 08.00	+44
St. Peterburg 19.00	+42
St. Petergurg 20.00	+45
St. Peterburg 21.00	+47
St. Peterburg 22.00	+48
St. Peterburg 00.00	+55
Hamina 08.00	-
Hamina 19.00	-
Hamina 20.00	-
Hamina 21.00	-
Hamina 22.00	-
Hamina 00.00	-
Hamina 01.00	-
Hamina 03.00	-
Hamina 05.00	-
Helsinki 01.00	-
Helsinki 03.00	-
Helsinki 05.00	-
Helsinki 08.00	-

Measurements between Estonia and Finland on 16-18 May 2006

The measurement track between Estonia and Finland is presented in Fig. 1. Two dual-frequency GPS-receivers set up on board a ferry were used for the measurements (Trimble R8 and Trimble 5800). The receivers were placed on the right and left boards of the ferry. The use of two receivers simultaneously allowed the comparison and estimation of the measurement results.

Data from the Pernaja GPS base station, a part of the Finnish network of GPS permanent base stations, and from the dual-frequency Geotracer 3220 receiver situated in Toila, Estonia, were used in post-processing. Southern part of the route is post-processed from Toila and North part of the route from Pernaja base station (Fig. 10).

Tide gauge data were collected from Hamina and Helsinki in Finland and from Toila, Narva-Jõesuu and Kunda in Estonia. As the tide gauge data varied very little, by a maximum of 5 cm, during the measurements, no water tilt corrections were added to the GPS measurement results.

Fig. 10 presents the chart of the Kotka–Sillamäe track.

To improve the readability of the chart, 17 m was subtracted from the heights measured by the Trimble 5800 receiver and 17.5 m from those measured by the R8 receiver. As for the most part the Sillamäe–Kotka ferry line runs parallel to geoid NKG04 contours (Fig. 1), the height change is not so drastic; nevertheless, it follows the same trend as in all the earlier measurements. The lack of data in Fig. 10 is due to the kinematic data processing software ambiguity solutions yielding no solution in the middle of the Gulf of Finland.

The data (heights) from the two GPS receivers used on the ferry show identical sharp protrusions, which invite a conclusion that they have to do with sea surface peculiarities or external disturbances in these particular areas rather than with GPS measurement errors. The protrusions were observed in exactly the same places irrespective of whether the ferry was bound for Estonia or Finland. The sharp changes in height (10–40 cm) occurred over short distances (1–6 km).

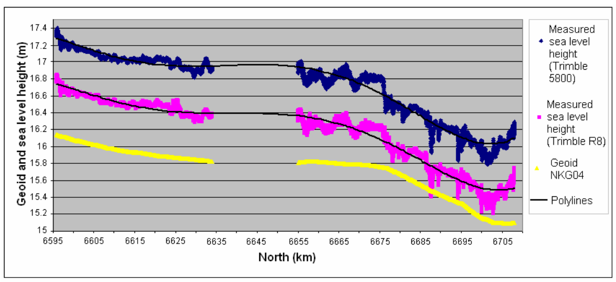

Fig. 10. *Water level relative heights by kinematic GPS between Sillamäe and Kotka, 18 May 2006. (6655 km responses to latitude ~60°). (Scale is slightly distorted, while only north component is used).*

The accuracy of the GPS measurements

We calculated some profiles from different base stations. An example is given in Fig. 11.

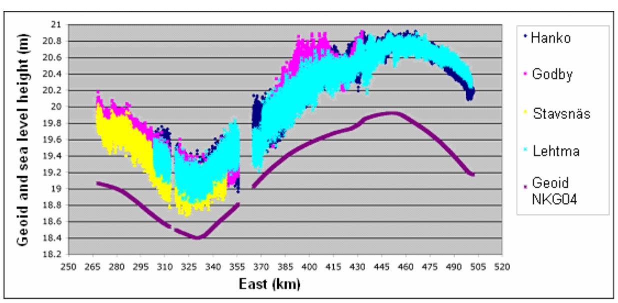

Fig. 11. *Water profiles calculated from different GPS base stations (Hanko, Godby, Stavsnäs, Lehtma) (Liibusk, 2005).*

Between Estonia and Sweden, the different GPS stations yielded results that were close, with the vertical component remaining within the range of 10 cm. The distance between the base stations was in some cases more than 80 km.

Conclusion

Using GPS kinematic measurements, some water level profiles were measured on the sea. The kinematic method with post processing was used. The water tilt effect was eliminated inasmuch as possible using different tide gauge data. The GPS measurements yielded results with the accuracy of about 6 cm; the regional water tilt effect could not be completely removed. However, the results showed a profile similar to that of Geoid Model NKG04 within the bounds of 15 cm. Consequently, we did not discover any big or remarkable differences between the measured level surface and the NKG04, even in areas for which the gravity data was of low quality or missing altogether.

Acknowledgment

We are thankful to the companies Geotrim OY in Finland and SWEPOS in Sweden, who supplied us with GPS base stations data, and to the Estonian Science Foundation, who financed the research under Grant 5731.

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GEOID AND GEOID-TYPE SURFACES DETERMINATION IN NORWAY

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The wide spread use of GPS for precise height determination has established quasigeoid/geoid estimation as a practically relevant product of physical geodesy. Civil engineers use the geoid as the reference surface for elevations while oceanographers use it for studies of ocean circulation, currents and tides. It is valuable to geophysicists for geodynamics studies, geophysical interpretation of the Earth's crust, and prospecting. These types of applications require knowledge of the geoid with a precision of ±1-10 cm. The new technologies of satellite altimetry and satellite positioning have placed a high demand on precise geoid determination research. Over the last decade, there has been an increased interest in the determination of the geoid. This is mainly due to the demands for height transformation from users of GPS. This procedure replaces costly conventional levelling operations with quicker and cheaper GPS surveys, as long as the geoidal heights have been computed to a high accuracy. Therefore, there is a common goal among geodesists to determine a "1-cm geoid model". A gravimetric quasigeoid/geoid is used by a surveyor to transform GPS ellipsoidal heights into normal/orthometric heights above the mean sea level. However, the quasigeoid/geoid does not exactly coincide with the height datum used for the normal/orthometric heights. This is due to a combination of the approximations used in the quasigeoid/geoid computation, systematic errors in heights and gravity data, and the exact definition of the height system. Currently, a surveyor using GPS and a quasigeoid/geoid must apply further data reductions in order to make his/her elevations compatible with the height datum. To obtain high accuracy levels for the computation of the geoid, terrestrial gravity observations as well as satellite observations in a combination with a global geopotential model are employed, utilizing a modification to the original Stokes formula. This study focuses on the impact of the different types of modification of Stokes's formula and different Global Geopotential Models to the resulted geoidal heights. These different parameters are investigated numerically over Norway. A new quasigeoid model for Norway is the result of these investigations. Also a new quasigeoid-type surface is determined to incorporate the gravimetric information of a quasigeoid model as well as the information obtained through GPS measurements on levelling benchmarks. This new surface is suitable for levelling by GPS. Different combining procedures, the least-squares collocation, the parametric models, as well as a wavelet-based model were investigated and compared over Norway. 1724 GPS-levelling stations were used. The best solution provided a quasigeoid-type surface with an accuracy of better than 3 cm.

ALTIMETRY-DERIVED MARINE GRAVITY ANOMALY AND ITS IMPACT TO THE GEOID OF NORWAY

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Free air anomalies (FAA) have been widely used in geosciences for many purposes. In geodesy and geophysics, FAA are used to compute a fine resolution and precise geoid surface. While land gravity data are collected accurately using precise gravimeters in a static way of measurement, the precision is degraded over sea to few mGals because of errors and biases due to dynamic behaviour of sea and kinematic measurements. Satellite altimetry missions have provided an alternative way for computation of FAA over seas. Data provided in this way can be integrated with marine and airborne data to increase the resolution of data, improve the precision and fill gaps. Free-Air Anomalies (FAA) in the waters around Norway including some parts of the North Sea, the Norwegian Sea and the Barents Sea are computed from satellite altimetry data. 84 cycles of ERS2 along track data, 25 cycles of ENVISAT along track data and high density ERS1 data during its geodetic mission are used. The new geopotential model from the Gravity Recovery and Climate Experiment (GRACE) mission (GGM02S) is used to compute long wavelengths contributions of geoid and FAA. To correct data for mean dynamic topography, the available Levitus climatology model is used. Corrected data are then used to compute along track gradients in each cycle-pass to suppress the orbital and the atmospheric errors below the noise level of the altimeter. Resulted gradients are then stacked and the east-west and the north-south components of the deflection of verticals are computed where ascending and descending tracks meet each other. Finally, inverse Vening-Meinesz formula is implemented on the gridded deflections to compute FAA. Results are then compared with available marine and airborne data. Standard deviations of ±4.301 and ±6.159 mGal in comparison with airborne and marine FAA were achieved. Thereafter, derived anomalies are combined with marine and airborne FAA together with the land FAA to compute a fine resolution geoid over Norway and the waters around. This geoid is evaluated over sea and land with synthetic geoid (derived from mean sea surface and mean dynamic topography) and Global Positioning System (GPS)-levelling. The standard deviations of ±20.9 and ±12.8 cm are observed, respectively. Results are then compared using available marine and airborne FAA and thereafter used along with land, marine and airborne FAA to compute a high-resolution geoid over Norway.

Local geoid modelling used to illustrate improved GGMs

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New global geopotential models (GGM) have been computed by several different institutes, e.g. GFZ and CSR, based on data from the satellite missions GRACE and CHAMP. These new models may be divided into two subgroups, models based on satellite data only and models based on a combination of satellite and surface gravity data.

In this work we investigate whether the new GGMs give better representation of the long wavelength part of the Earth's gravity field.
This is done by comparing local gravimetric geoid models to a synthetic geoid model. The local gravimetric geoid models are computed using local gravity data with a selected GGM as reference field. The Stokes kernel is also modified using the Wong-Gore approach.

Local gravimetric geoid models using GGMs based on GRACE data as reference field give significantly better results than using either
EGM96 or CHAMP. The best results are obtained in combination with a modified Stokes kernel truncated at degrees 90 - 95. Using EGM96 as a reference field smallest standard deviation is obtained with Stokes kernel truncated at degree 30. This indicates that the new GGMs give a better representation of Earth's gravity field.

The EUVN_DA GPS campaign in Finland in 2005.

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Abstract

The original EUVN (European Vertical Network) campaign was performed in 1997. The initial practical objective of the EUVN project was to unify different European height datums. The network of 12 permanent GPS stations, *FinnRef®*, was already working, but only 5 of the stations were accepted in the campaign.

In 2002 the EUREF commission initiated the EUVN_DA campaign (Densification Action). A large number of the GPS/levelling points, which were measured in Finland 1995-1999 did not fulfil the requirements stated for the EUVN_DA stations. The number of the accepted station was only 20, which was regarded too low.

The GPS observations for the densification of the EUVN-network were made in July-Aug. 2005. The observation sites were precise levelling benchmarks or new benchmarks, which were levelled before GPS observations. During the campaign 30 new GPS/levelling sites were observed. The nominal GPS observation time was 24 hours.

The GPS observations were processed using the Bernese 5.0 software. The Finnish permanent GPS network *FinnRef®* (12 stations) served as backbone for the GPS solution of the coordinates. Besides, the GPS observations from the new private GPS network, *GPSNet* (84 stations), were used in the solution. The computations were made in the ITRF2000 frame using the 4 Finnish EPN stations and Kiruna and Tromsø as fiducial stations in the solution. The estimation of the accuracy of the coordinates of the new sites were made according to the discrepancies between consecutive half day solutions. The RMS values of the deviations were ± 3 mm, ± 3 mm and ± 6 mm for N, E and U components, respectively.

The EUVN Campaign

The initial objective of the EUVN project was to unify different European height datums. The proposal for the campaign was presented by Ihde and Schlüter in the EUREF meeting in Helsinki in 1995.

The GPS observations for the EUVN were carried out in the period from May 21 to May 29, 1997. In total the EUVN consists of about 196 sites: 66 EUREF and 13 national permanent sites, 54 UELN and UPLN (United Precise Levelling Network of Central and Eastern Europe) stations and 63 tide gauges. (Ihde et al. 2002).

The number of sites accepted in the EUVN campaign in Finland was 10. They consisted of 5 permanent GPS stations and 5 tide gauges (Fig. 1). During the campaign the Finnish network of 12 permanent GPS stations (*FinnRef®*), was already working, but only 5 of these stations were accepted in the EUVN campaign.

The results of the campaign were accepted as a class B extension to the EUREF89 network in the EUREF symposium held in Prague in 1999 (EUREF 1999). The results were published in two volumes in 2002 (Ihde and Sacher 2002).

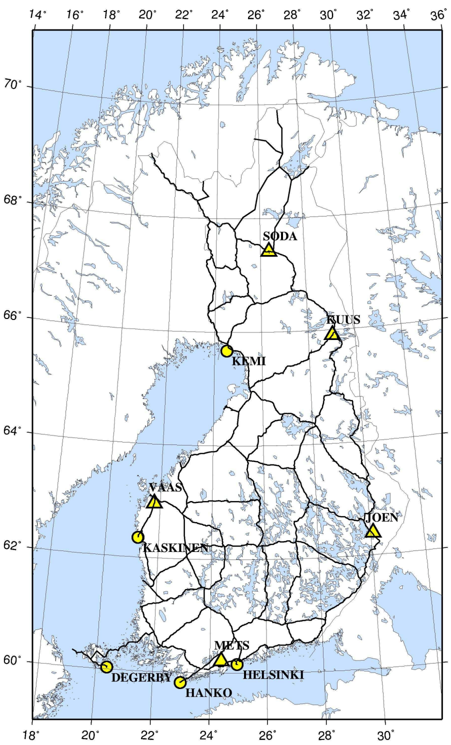

Fig. 1. The EUVN stations observed in 1997 and the Precise levelling network. The permanent GPS stations are marked with triangles, the tide gauges are marked with circles.

The densifications of the EUREF network in Finland

During the years 1996 and 1997, GPS campaigns called EUREF-FIN were performed, where the FGI measured a network of 100 points over Finland. The permanent network was a part of this campaign.

The main part of the observation sites was first order triangulation points. In order to connect the GPS network to the national orthometric height system (N60), some tide-gauge sites and precise levelling benchmarks were included in the network.

The GPS observations were carried out using six field receivers. The 12 stations of the Finnish permanent GPS-network *(FinnRef®)* served to define a reference frame, ITRF96, throughout the campaigns. In the final computation the coordinates were transformed to coincide with the ETRF89 frame (Ollikainen et al. 2000).

Results of the EUREF-FIN campaign were presented in EUREF meeting in Prague 1999. A subset of the sites was accepted as class B extension to the EUREF89 network (EUREF 1999).

Definition of the EUREF-FIN reference frame is done with the permanent GPS network *FinnRef®* and the network of the 100 points. In 1998-1999 FGI densified this network by measuring 350 points in order to offer an easier accessible points for practical use. Points were selected mainly from lower order points of the National Land Survey.

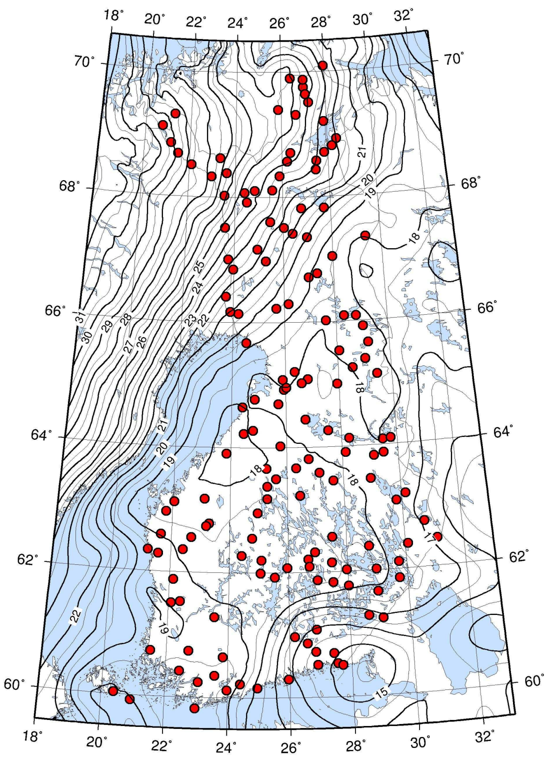

Fig. 2. *TheGPS/Levelling stations used for the determination of FIN2000.*

The selection criteria were accessibility and good GPS visibility. (Ollikainen et al. 2001, 2002). The campaign comprised 344 additional densification stations, which were mainly measured for surveying purposes. The nominal observation time, 6 hours, was shorter than in the EUREF-FIN campaign. The final adjustment resulted the following values for the RMS accuracy of the coordinates: ± 4 mm (North), ± 4 mm (East), ± 6 mm (Up). Because the coordinates of the *FinnRef®* stations and the EUREF-FIN points were held fixed in the final adjustment of the coordinates, the coordinate system of the second phase densification is ETRS89 in the epoch 1997.0.

Large number of the EUREF densification sites (154) were also levelling points in the precise or lower order levelling. These points were used to determine the Finnish geoid model, or preferably a transformation surface. The FIN2000 geoid model and the GPS stations used in the determination are shown in Fig. 2 (Ollikainen 2002).

The EUVN Densification Action (EUVN_DA)

The EUREF meeting held Tromsø, 2000 noticed that the density of the EUVN sites was not sufficient and asked the relevant authorities to densify the network of EUVN GPS/levelling geoid heights (EUREF 2000).

In 2002 the EUREF commission initiated the EUVN_DA campaign (Densification Action). The EUVN_DA will serve e.g. as a base for:

– geoid improvement on the continental and national levels

– better information on the national height datum differences,

– an improved continental reference for GPS-heighting (Kenyeres et al. 2003)

According to the original plan the maximum site separation should be less than 100 km (50 km was considered to be optimal) corresponding to at least one point per 10000 km^2. The GPS-observation time at a densification site was expected to be at least 24 hours. The GPS markers should be linked to the nearest UELN nodal point, and the gravimetric measurements should be also performed to derive geopotential numbers.

The action was planned to carry out in 2 phases. The first phase was planned for collection of the existing GPS and levelling data. The Phase II was devoted to the establishment and measurement of new sites. The proposed deadline for the completion of the EUVN_DA database was 31 May 2005.

The schedule showed to be too tight for some countries and the deadline for the Phese II was moved one year further until April 2006 (Kenyeres and Sacher 2005).

The Finnish action for the EUVN_DA

Although we had in Finland a large number of GPS/levelling points, which were observed in 1996-1999 (Fig. 2), it turned out that among these sites there were only very few, which fulfilled the requirements stated for an EUVN_DA station. During the invention phase we found out besides the original

EUVN station only 10 additional GPS sites. The original EUVN stations and accepted EUVN_DA stations are shown in Fig. 3.

The new EUVN_DA stations

The new stations EUVN_DA sites were selected in 2004. At first the new sites were tried to locate close to the nodal points of the precise levelling network.

The levelling benchmarks are in many cases located in places suitable for spirit levelling, but impossible for GPS observations, i.e. in places where a large part of the sky is obscured by trees, buildings, electricity transmission wires etc. This is why we had to establish new markers in the vicinity of the levelling benchmarks where GPS observations were performed. The height differences between auxiliary markers and levelling benchmarks were determined by spirit levelling. A typical distance between levelling benchmark and auxiliary marker was 50-100 m.

During the reconnaissance of the new sites the total number of the visited levelling sites was approximately 300. The number of new benchmarks established was 11, while the old benchmarks could be used in 19 cases for GPS observations. The location of all new EUVN_DA sites are shown in Fig. 4.

The permanent GPS stations in the campaign

The coordinates resulting from various GPS campaigns could be connected to the same coordinate frame using the same GPS stations as the fiducial stations in the ccampaigns. In our case the Finish EPN stations were used as fiducial stations in the EUVN campaign in 1997. (Ineichen et al. 2002). Besides the Finnish stations used in the north-est parts of the network the Swedish EPN station Kiruna (*SWEPOS*) and the Norwegian EPN station Tromsø (*SATREF*) as fiducial stations.

The distances from the fiducial stations to the new EUVN_DA sites are hundred of kilometres, even if all *FinnRef*® stations are used in the campaign. A private enterprise *Geotrim Ltd.* established in 2004-2005 another network og permanent GPS stations in Finland. The network, *GPSNet*, was established mainly for GPS positioning using Virtual RTK System (VRS). The network, which comprises 8 stations distributed over whole country, is working continuously by recording interval of 1 sec (Trimble Navigation Ltd. 2006).

In order to get the baselines between the permanent GPS stations and the EUVN_DA sites as short as possible all *FinnRef*® stations and *GPSNet* stations were taken in the campaign. The number of permanent stations used in the campaign was 98. The distribution of the permanent GPS stations is illustrated in Fig. 5.

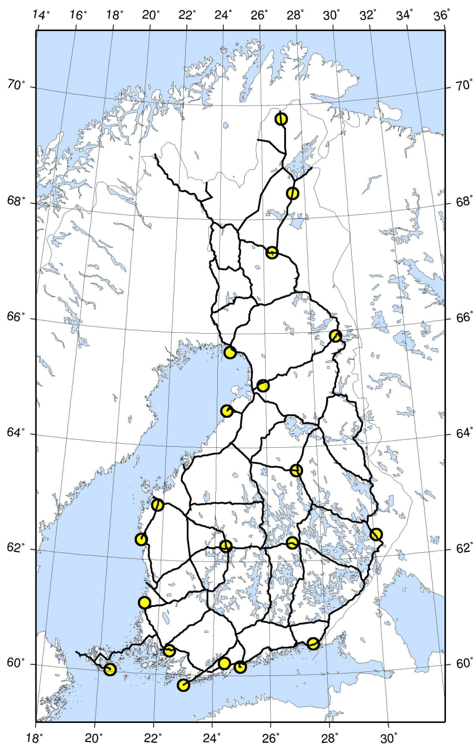

Fig. 3. *The Finnish Precise levelling network. Circles represent the accepted (2002) EUVN_DA stations.*

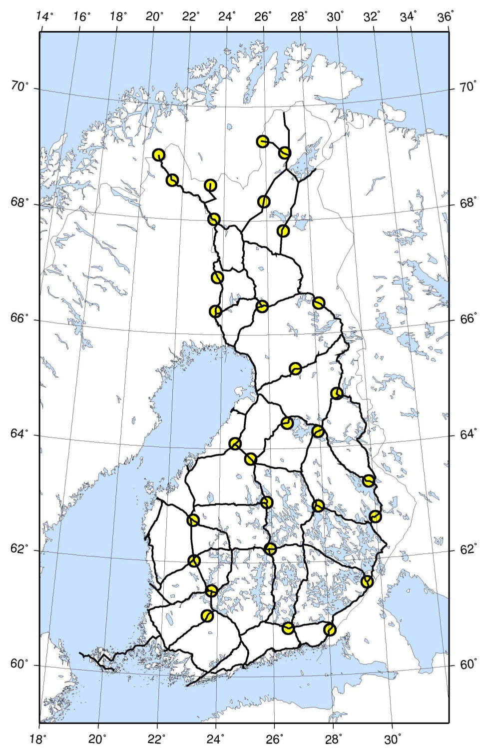

Fig.4. *The new densification stations and the Finnish precise levelling network.*

Observations at the densification sites

The field observations took two weeks, GPS days from 207 to 221. The field observations were made using 4-5 Ashtech Z-12 receivers, equipped with Dorne Margolin type choke ring antennas. The nominal observation time was 24 hours. he observation session started at noon local time and stopped at noon next day.

The GPS antennas were mounted over the benchmarks using tripods. In each station the antennas were set centric on the benchmark. The antenna heights were measured in the beginning and at the end of the session and checked once in the middle of the session.

After the session all receivers were moved to next sites. The permanent GPS stations served the link between the consecutive sessions.

Reduction of GPS observations

The data of the whole campaign consisted of 15 days recordings at 98 permanent GPS stations (DOYS 207-221) and 30 one day recordings at the EUVN_DA sites. Altogether the GPS data consisted of 1500 days recordings at 30 sec. interval. Converted to the RINEX format the volume of the data was approximately 4 GB.

The Bernese version 5.0 software (Hugentobler et al. 2004) was used for the processing. The processing was made in the ITRF2000 coordinate frame, the epoch of the observations was 2005.58. The fiducial stations used in the reduction were the Finnish EPN stations Metsähovi, Joensuu, Vaasa and Sodankylä, Swedish EPN station Kiruna and Norwegian station Tromsø. The coordinates for the fiducial stations were taken from (IGS 2005a) and reduced to the epoh of the observations using the velocity components for the stations, which were given in (IGS 2005b).

The computation procedure for the GPS baselines was following: program CODCHK was run first to eliminate obvious outliers from the code observations. The baselines were selected so that there were no trivial vectors in the daily networks. The baselines solved for the network are shown in Fig. 6. The phase differences were created for the selected baselines, after which the cycle slips were removed by running the program MAUPRP twice. The cut-off angle was set to 5°.

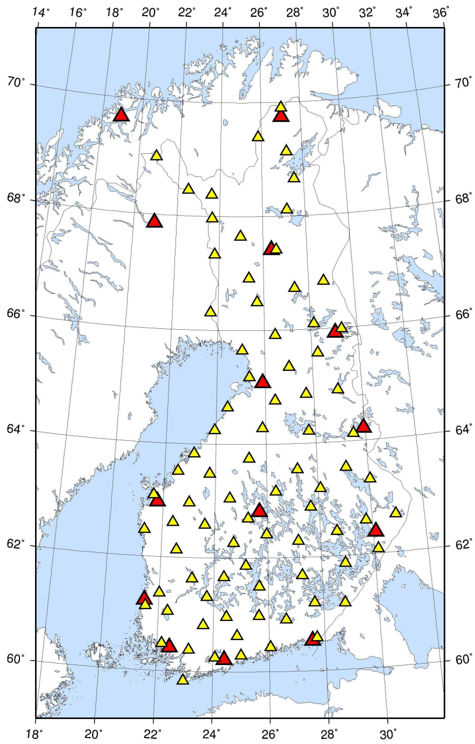

Fig. 5. *Permanent GPS stations. Filled triangles: FinnRef®+SATREF+SWEPOS Open triangles: GPSNet.*

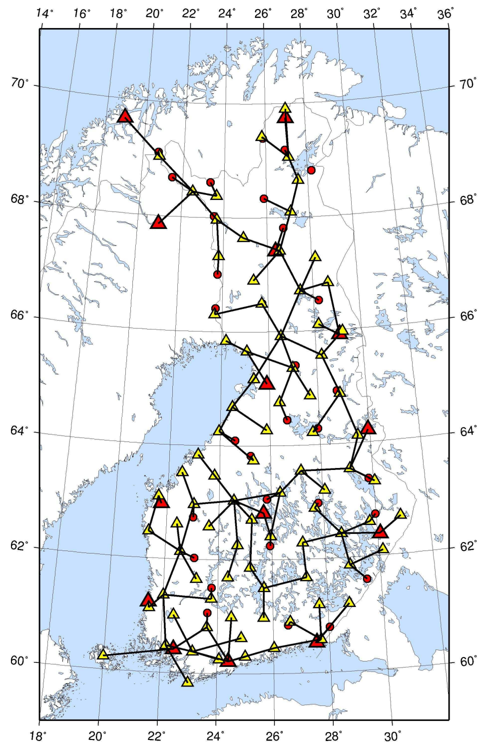

Fig 6. *The network measured in July-Aug. 2005. The GPSNet stations were used as intermediate stations.*

The program GPSEST was used for parameter estimation. First, the ambiguities were resolved baseline-by-baseline using the QIF (Quasi Ionosphere Free) method (Mervart 1995) and fixing one end of the baseline. The coordates of the vector's other end, one troposhperic zenith delay parameter for 2 hours, and ambiguities were resolved and saved to the data file. Wet Niell mapping function used in the solution of the site specific troposphere parameters.

The GPSEST program was then run again using L3 linear combination and pre-eliminating the remaining ambiguities. The daily solutions were saved in the form of normal equations for the next step.

The network adjustment was made using the normal equations from the baseline solutions according the following principles:

1. The coordinates of the *FinnRef®* stations were solved first constraining the EPN stations to their ITRF2000 coordinates. The daily solutions were combined using the program ADDNEQ.
2. The daily sessions, which comprised of the data from the *FinnRef®* stations, *GPSNet* stations and EUVN_DA sites were combined using the program ADDNEQ by constraining the coordinates of all EPN and *FinnRef®* stations to their ITRF2000 coordinates,
3. The final adjustment of the all daily solutions using the program ADDNEQ.

Accuracy of the GPS positioning

The RMS values of all coordinate differences between the daily solutions and the final solution may be considered as an overall accuracy measure of the campaign. These RMS values are ± 3 mm, ± 3 mm and ± 6 mm in the North, East and Up component, respectively.

Definitive coordinates

Finally, the coordinates were transformed from ITRF2000(Epoch:2005.58) to ETRF89(Epoch:2005.58). This was done, following the recommendation of the EUREF subcommission, according to the formula by Boucher and Altamimi (2001):

$$\mathbf{X}_{\mathbf{ETRF89}}(t_C) = \mathbf{X}_{\mathbf{ITRFyy}}(t_C) + \mathbf{T}_{yy} + \begin{vmatrix} 0 & -\dot{R}3_{yy} & \dot{R}2_{yy} \\ \dot{R}3_{yy} & 0 & -\dot{R}1_{yy} \\ -\dot{R}2_{yy} & \dot{R}1_{yy} & 0 \end{vmatrix} \cdot \mathbf{X}_{\mathbf{ITRFyy}}(t_C) \cdot (t_C - 1989.0)$$

The parameters used in the formula above are given by Boucher and Altamimi (2001):

$$\begin{cases} Tx_{2000} = 5.4\,\text{cm} \\ Ty_{2000} = 5.1\,\text{cm} \\ Tz_{2000} = \text{-}4.8\,\text{cm} \end{cases} \qquad \begin{cases} \dot{R}1_{2000} = 0.081 \; [0.001''/y] \\ \dot{R}2_{2000} = 0.490 \; [0.001''/y] \\ \dot{R}3_{2000} = \text{-}0.792 \; [0.001''/y] \end{cases}$$

The formula reduces the coordinates from ITRF2000 (Epoch: 2005.58) to ETRF89, but the epoch of the coordinates remains unchanged, because no reduction for the movement of the stations in the reference frame was made. While being a recommendable procedure, there is the problem that the velocities of stations on the Fennoscandian Shield contain a contribution from the postglacial rebound. The time interval 1989-2005 is already so long that this phenomenon cannot be ignored, and would have to be modelled somehow, if we were to use model velocities.

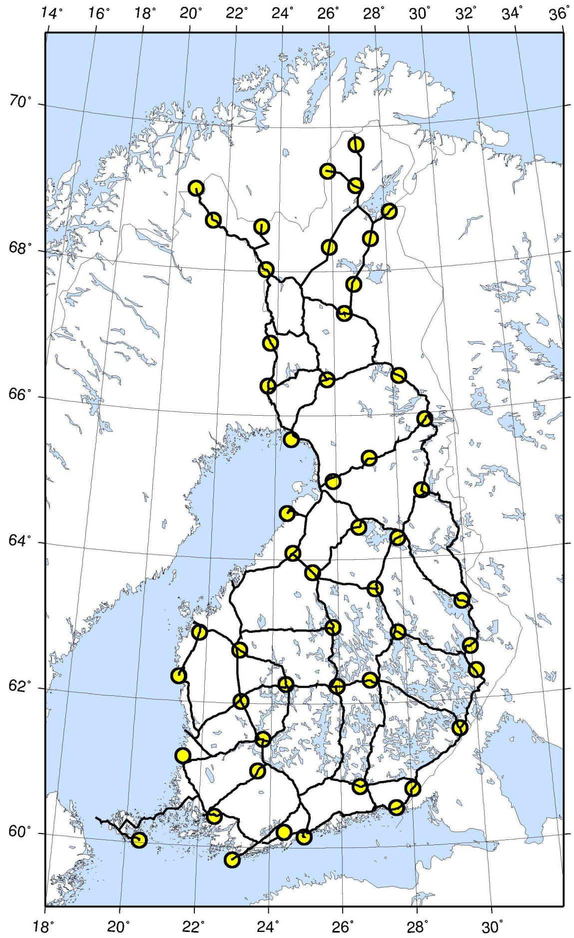

Fig. 7. *The precise levelling network and the EUVN_DA stations after the densification in 2005.*

Conclusions

The first group of the EUVN_DA points was measured in 1996-97 (Epoch: 1997.0). The epoch of the last measured points is 2005.58. The coordinates were transformed to a common reference frame (ETRF89), but the transformation shown in the previous chapter does not take into account the intra-plate deformation, which has happened between the observation epochs. In the Nordic countries such deformation is caused e.g. the post-glacial rebound. During the time elapsed between the observation epochs (8.6 years) the post-glacial rebound cause changes, which may reach 7-8 cm in the heights of the stations.

It is obvious that the coordinates, which are measured in different epoch, should be reduced to a common epoch using a reliable velocity model, before using them together for a common purpose. When the GPS solution of the Finnish EUVN_DA campaign was completed, in the spring 2006, we had not made a decision, which model should be used for the reduction of the coordinates to a common epoch. Probably, in the EUREF meeting in Riga, June 2006, the question will be discussed, and the velocity model will be chosen.

Acknowledgements

Large amount of the GPS data used in this campaign was recorded at the *GPSNet* stations, which are run by GEOTRIM Ltd. According to the agreement between FGI and GEOTRIM Ltd. FGI could use the data for this project witout any costs.

The author is acknowledged to Mr**.** *Seppo Tötterström*, GEOTRIM Ltd., for supplying the GPS data from the *GPSNet* stations.

Mr. *Pekka Lehmuskoski*, *FGI*, took part to the reconnaissance of the new GPS sites. Besides, he mounted the new benchmarks to the bedrock and leveled them. I am deeply indebted to him for the work.

Mr. *Pasi Häkli, FGI,* made the preprocessing of the GPSNet data. He also took part in the GPS observations in the field. His contribution is highly appreciated.

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The Accuracy of Height Models Derived by Auto-Correlation from Digital Aerial Images Obtained by a Vexcel Large Format Digital Camera.

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KMS, The National Survey and Cadastre - Denmark initiated project 'digital aerial camera' in cooperation with Danish National Space Center, Blom Info and COWI A/S. Both Blom Info and COWI are large mapping companies both using Vexcel UltraCamD digital cameras for use in there mapping and ortho photo production. The project is still ongoing and are investigating various issues of influence using large frame digital cameras compared to standard analog film cameras.

As a digital frame image is rectangular, and not square as a film image, the base/height relation will decrease the geometry (Figure 1) and in that way maybe also decrease the height determination by auto-correlation. However investigations by the project participants will show that this is not the case and images from digital cameras are as good as film cameras for height determination issues. Further will the digital cameras provide the users with an increasingly amount of information due the better radiometry and clarity.

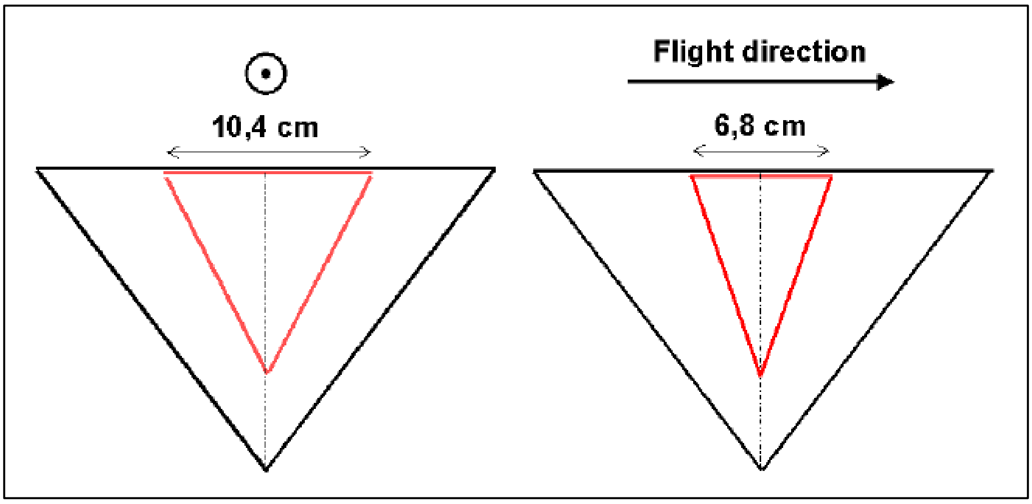

Figure 1. *Across track and along track geometry of the digital Vexcel UltraCamD (shown in red) compared with a traditional 150 mm focal length analogue film camera.*

Precise Levelling Campaign in Estonia

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Network configuration

The Estonian precise levelling network (Fig. 1) with slight modifications repeats the network established by Department of Cadastre in 1933 – 1943 and remeasured by the Estonian Academy of Sciences and Soviet organizations in 1948 – 1991 (Table 1). Lines in the West-Estonian islands were added during the Soviet period.

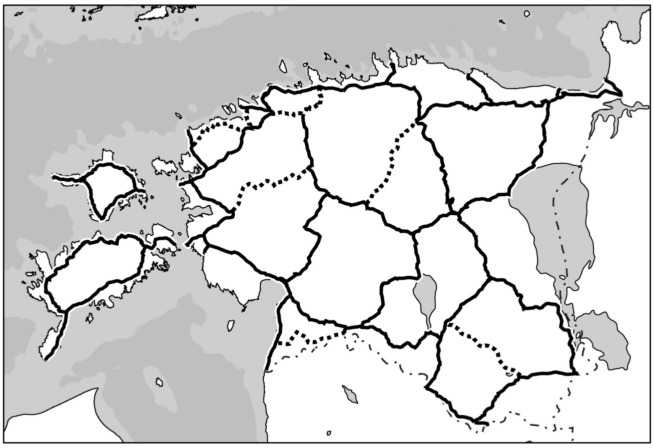

Fig. 1. *The Precise Levelling Network of Estonia. The new lines are dashed.*

	Period of levelling	Length of the levelling lines [km]	Random errors, η [mm/km]	Systematic errors, σ [mm/km]
1	1933 – 1943	6 loops in mainland, 1814	0.32	0.03
2	1948	Line Narva – Tallinn – Ikla, 505	0.50	0.05
3	1970	Line Narva – Tallinn – Ikla, 574	0.53	0.06
4	1981 – 1983	1380	0.71	0.10
5	1951 – 1969	2067	0.48	0.08
6	1970 – 1991	2208	0.46	0.04

Table 1. *Levellings performed in 1933 – 1991.*

1 Department of Cadastre, Estonian Ministry of Agriculture
2 – 4 Main Board of Geodesy and Cartography, USSR
5 – 6 Institute of Astrophysics and Atmospheric Physics, Academy of Sciences

Some of the lines were measured more frequently in order to study the differential movements of the blocks of the crystalline basement. The network was extended to the West Estonian islands in 1940, 1958, 1963, 1971, 1979, 1980 and 1981 using different techniques: geometric levelling, hydrostatic levelling and sea level observations. The details can be found in Tamm (1988) and references therein.

Lines of the new network were planned to be located along roads, for this reason the lines in the North-East and in the South-East of Estonia along railway lines were replaced. The network was densified in some regions (Fig. 1, dashed lines). The lines with the total length of about 2900 km form 15 polygons, 13 in the Estonian mainland and 2 on the West – Estonian islands.

Reconstruction of the network, Fourth Levelling of Estonia considering the accuracy and periods of early measurements, is carried out under the contract with Estonian Land Board.

Preparation of lines

The wall benchmark of 1930´ies inside the living room in 2005.

By the reports of inspection about 50 % of old benchmarks are destroyed. Some of them, still existing, are not usable because of location, stability or construction. Those are the main reasons, not the precision of early levellings, for new campaign.

Because in Estonia the bedrock is located at great depth, the use of it for monumenting is very complicated or impossible. For the reason the soil is used for monumentation. When the soil is used, the deformation it's seasonally freezing (lifting of the benchmark) and deformation under the benchmark (sinking of the benchmark) should be considered. Wherever they were near the surface, the solid sedimentary rocks (limestone, sandstone, dolomites) were selected for monumentation.

In Fig 2 the construction of fundamental and ground benchmarks is shown.

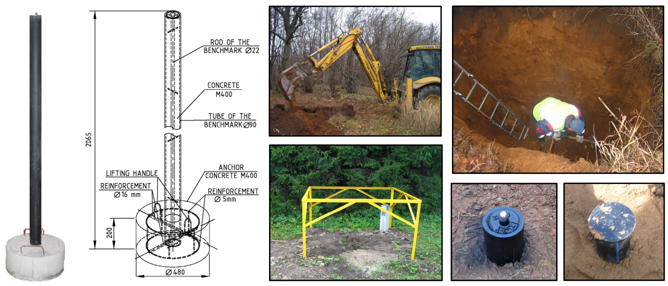

Fig. 2. *Construction of new fundamental and ground benchmarks.*

For a low thermal conductivity and friction drag, a tube of the benchmark was made from plastic. Stainless steel was used for the inner rod.

Fig. 3. *Wall benchmark.*

In case of stable buildings available, the wall benchmarks (Fig. 3) were established. They are made from stainless steel and painted for security reason.

About 2100 km of lines have been prepared in the Estonian mainland since 2004. Distance between the benchmarks, altogether 1302, is 2 km on average. From the benchmarks 599 are new. Preparation of lines in the West – Estonian islands will be completed in 2006. Some new lines in the Estonian mainland will be added in 2007.

Concept of the Integrated Georeference

It can be shown that the integrated use of different geodata provides qualitatively new results. According to the Concept, developed in 1996 (Rüdja 2002a, 2002b), the Integrated Georeference in Estonia connect the networks of different kind for combination and for the long term monitoring of geometrical and physical observables with emphases on scientific use and on practical georeferencing. Establishment of the Integrated Georeference started with reconstruction of the National Geodetic Network performed by us in 1996 – 1998.

Into the lines of precise levelling in the Estonian mainland 338 points of the National Geodetic Network and Densification Network, 52 points of the gravity remeasurement network and 9 tide gauges stations are included. They are shown in Fig. 4 – 6, respectively. Distance between the "GPS points" included is about 5 km.

Levelling

Reconstruction of precise levelling network started with the pilot project carried out by company working under the contract with ELB in 2001. Based on project the main aspects of the levelling technology were developed.

The technique applied is the conventional foot levelling (double run). Zeiss/Trimble DiNi 12 digital levels and invar staffs from NEDO are used. The rods and levels are regularly calibrated at the Finnish Geodetic Institute. In every second section the direction of levelling relative to the direction of the line is changed (A – B, B – A). The "Rote hose" method (BFFB – FBBF) is applied. The minimal sighting height is 70 cm and the maximum distance from the instrument to the rod is 40 m. Differences of sighting lengths are kept within 20 cm in stations and within 50 cm in sections. Period from September to December was selected as the only period for levelling. Depending on productivity requirements August much less suitable for precise levelling was included since 2005. For keeping of target accuracy the sighting lengths were reduced to 30 m and mid-day pause was extended to three hours in that case.

Air temperature, vertical thermal gradient, humidity, air pressure, wind speed and the temperatures of the invar scales are measured (Fig. 7). They are automatically stored using data loggers during the levelling. Additional data, like road characteristics and cloudiness of the sky etc., are recorded using pocket PC. Each single record is stored into the levelling database developed.

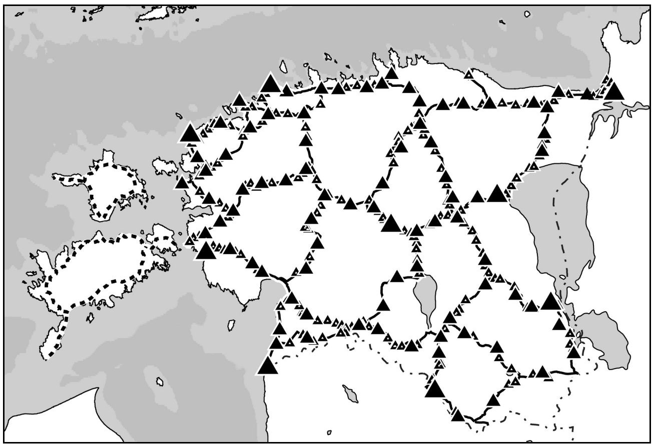

Fig. 4. *Points of the National Geodetic Network and Densification Network included into the levelling network in the Estonian mainland.*

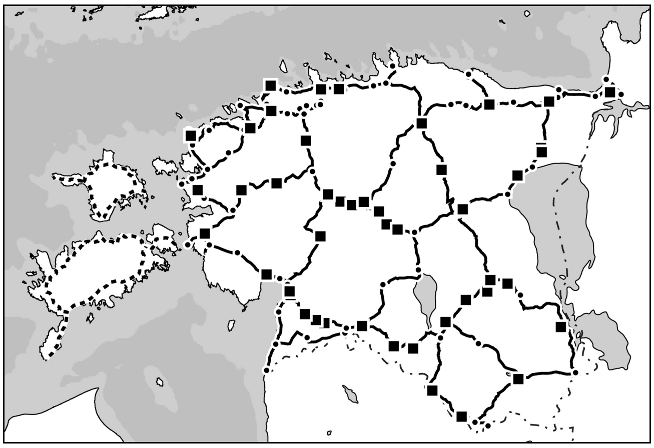

Fig. 5. *Points of the gravity network included into the levelling network in the Estonian mainland.*

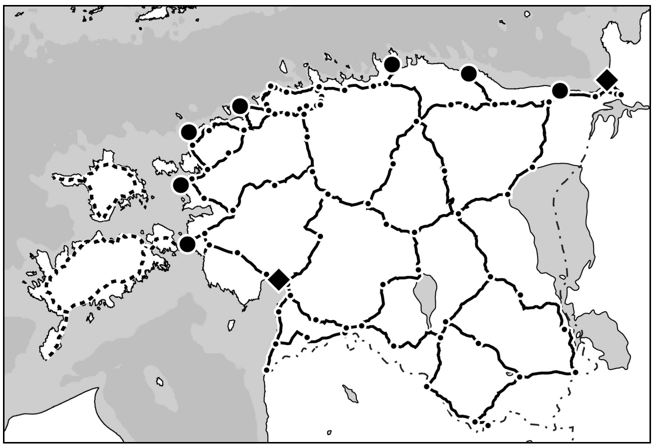

Fig. 6. *Tide gauge stations included into the levelling network in the Estonian mainland.*

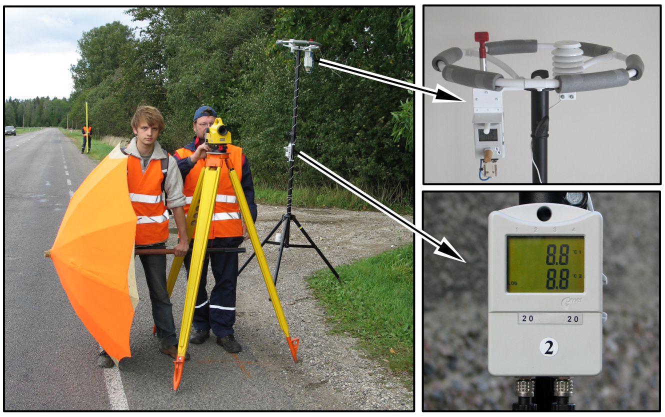

Fig. 7. *Levelling. The meteoinstruments in use.*

The technology was applied in measurement of precise levelling network of Tallinn in 2003 – 2004. Altogether 340 km were levelled (Fig 8) with precision comparable to estimation shown later on. Part of the network will be included to the state levelling network (Fig. 1) after completion. Levelling of main lines of the network started in 2004. Since that, more than 550 km have been levelled.

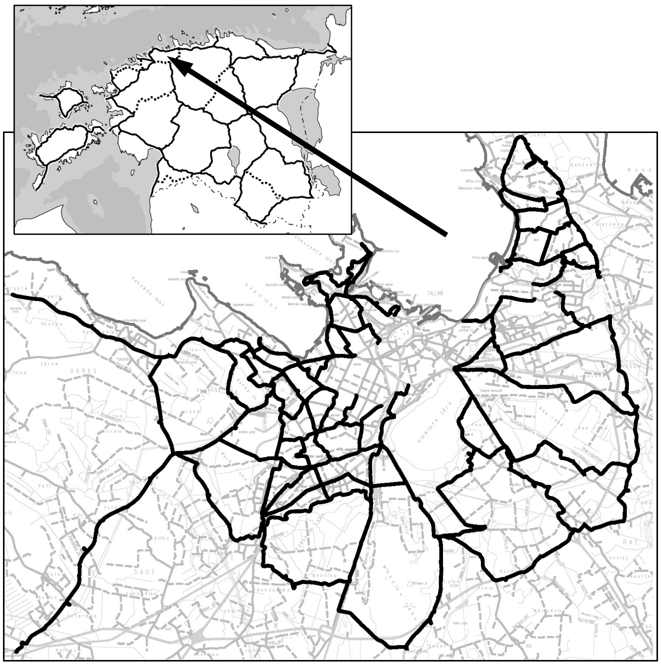

Fig. 8. *Lines of the precise levelling network of Tallinn measured in 2003 – 2004.*

In spite of sunny autumn in 2005, the inner consistency of measurements is promising. In Fig. 9 histogram of discrepancies in measured height differences in stations (BF minus FB) and in Fig. 10 normalized differences in sections (the differences between forward and backward levelling of the section divided by the length of sections) are presented. Those are based on 519 km double run levelling performed by the three field teams in 2005. Random and systematic errors calculated from the differences between forward and backward measurements (Jordan *et al.* 1956) are: η = 0.19 mm, σ = 0.04 mm. The misclousure in the two loops with perimeter of 281 and 300 km are -2.41 and -2.59 mm, respectively.

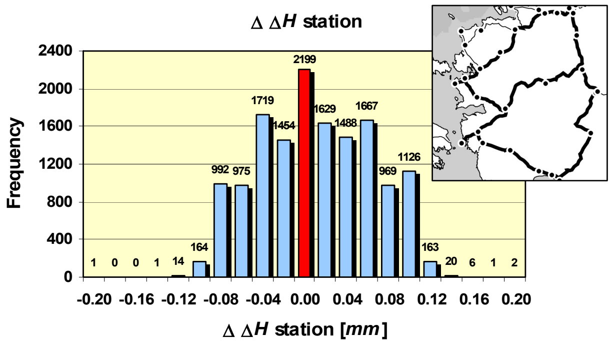

Fig. 9. *Distribution of discrepancies in measured height difference in stations.*

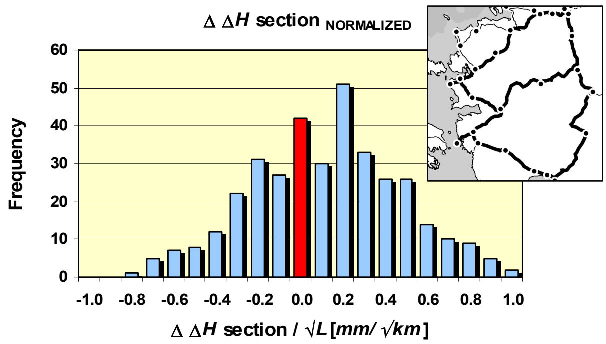

Fig. 10. *Distribution of discrepancies in measured height difference in sections (normalized).*

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On digital levelling technique applied in water crossing

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Keywords: Levelling, digital levelling system, sight distance, water crossing.

Summary

The digital levelling technique is commonly used in surveying today. The Zeiss DiNi12 levelling system is capable to operate when sighting distances are less than hundred meters. But longer sights are occasionally needed, e.g., in crossings over the lakes, valleys or rivers. The range of the system can be extended by enlarging a bar code scale. According to the preliminary tests the Zeiss DiNi12 was able to process rod readings at the distance of 400 m. A pair of rod scales with a magnification factor four was designed. In order to study the operation and accuracy of the modified Zeiss DiNi12 system a test field for water crossing was planned. The results proved that the developed digital water crossing method meets the standards of precise levelling. At the same time the trigonometric levelling method was also tested.

Introduction

At the beginning of the 90's the digital levelling became known as an effective tool for precise measurements. It was almost automated, accurate and quick technique (Ingensand, 1990). The optical characters, the size of the CCD-array and especially the size of the code element limited its maximum sighting distance to 100 m (Feist et al.,1999). In water crossing we need several hundreds meters or even kilometers long sighting distances. Applications of the digital levelling in water crossing have been examined in Japan, Germany (Schauerte et al., 1999) and in Finland since 2003 (Takalo and Rouhiainen, 2004a).

In Finland we have been studying the behavior of the Zeiss DiNi12 digital levelling system (Takalo and Rouhiainen, 2001). The remarkable advantage of Dini12 is that the software of the level uses a limited sector of the observed bar code scale to process the rod reading. This minimizes disturbing effects of partial code lines, shadows etc. By magnifying the size of the bar code element (20 mm), one can exceed the range of the system.

In this study we describe the tests of the DiNi12 digital levelling system in case of water crossing. By the side of the digital levelling we have also tested the trigonometric levelling.

Zeiss Dini12

The magnifying of the bar code scale influences linearly to the height and distance readings of the digital level (Schauerte et al., 1999), but does not change the magnifying ratio between the bar code and its projection on the CCD-array. We used black and white plastic tape to build up 4 x bar code scale, which was fastened on the backside of three meter long aluminium frame rod. To set each code element on its right place, we used measuring pieces of steel and a sharp-edged knife as a tool (Figure 1).

Fig. 1. *Producing of a magnified bar code using measuring pieces.*

Scale factors were determined by calibrating bar codes in the system calibration comparator (Takalo and Rouhiainen, 2004b). Thermal expansion coefficient was obtained by repeating the calibration at different temperature (t). The scale factor includes the length correction of the scale and the thermal correction (Table 1).

Table 1. *Scale factors of the 4x magnified bar codes.*

Instrument	Rod	Scale factor
320015	8617	$3.99990 + 21.6 \times 10^{-6}$ (t-20°)
320015	8618	$3.99982 + 22.2 \times 10^{-6}$ (t-20°)

Trigonometric levelling

The trigonometric levelling was used as a second method in the water crossing tests. The method developed in Finland (Takalo, 2000) is based on the use of two theodolites. The measurement consists of two basic operations: benchmark connection and height transfer (Figure 2). In the former the height difference between benchmark and the theodolite is determined by observing the vertical angles to the graduation lines on the rod which was set up on the benchmark. In the height transfer the height difference between two theodolites are derived from simultaneous and reciprocal observations of the vertical angles and slope distances to the targets and prisms of the theodolites, respectively (Figure 3).

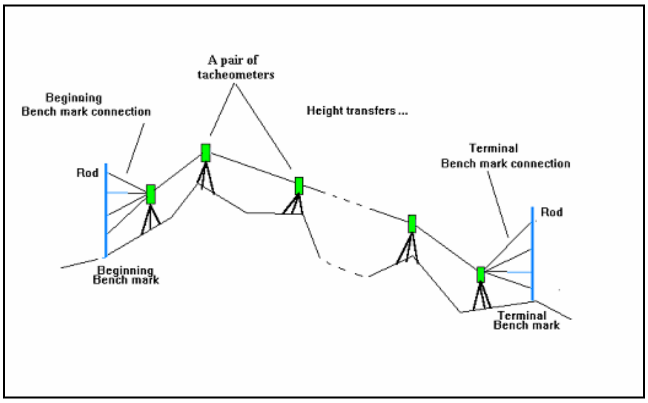

Fig. 2. *Principle of trigonometric levelling*

The measuring equipment consists of two electronic theodolites, a precise EDM instrument, an automated weather station, two radio modems and a field computer (Takalo, 1998). Two enlarged signals were used in water crossing mode of the trigonometric levelling (See, Figure 3).

Fig. 3. *Enlarged target used in water crossing tests in Otsolahti.*

The Otsolahti test field

To test water crossing methods a test field was established around the Otsolahti bay in the city of Espoo during 2003-2004. The basic field consists of three benchmarks in bedrock T1, T2 and T3 and auxiliary benchmarks T11, T21 and T31 also in bedrock (Figure 4).

The points T4 and T41 were established in 2005 only to test the trigonometric water crossing method. The distances as the crow flies and the height differences of the benchmarks are given in Table 2.

The circumference of the loop T1-T3-T2-T1 is 1035 m and there is an open view from each point to another, except of the point T4 is out of sight from the point T3.

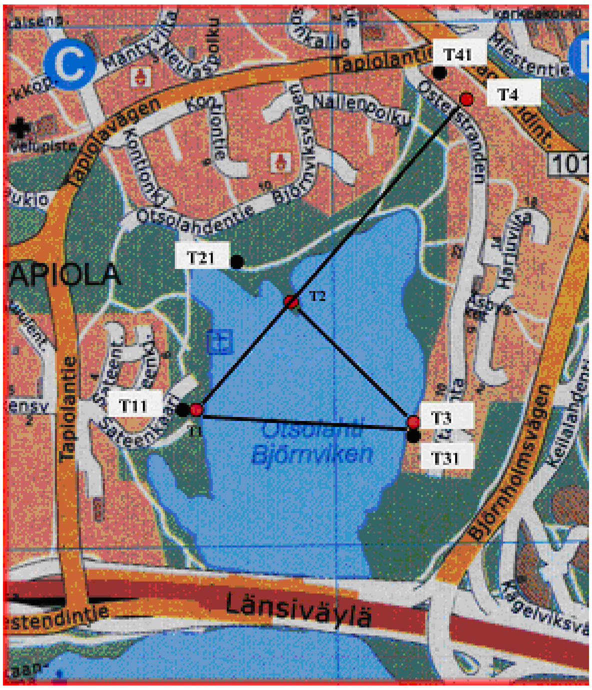

Figure 4. The Otsolahti test field for water crossing. The copyright© of the map is owned by the city of Espoo.

Table 2. *The distances and the height differences of the benchmarks in the Otsolahti test field.*

Interval	Distance	Height difference
T1 – T2	260 m	+0.29 m
T2 – T3	370 m	-0.11 m
T3 – T1	405 m	+0.18 m
T1 – T4	730 m	+3.83 m

Measurements

In order to create an accurate reference, i.e., true heights, the height differences between all benchmarks of the Otsolahti test field were measured using the precise levelling. The measurement with the Zeiss DiNi12 level and invar rods was done along the coastal walking paths of the Otsolahti bay (Figure 4) in 2004 and 2005. The standard error computed from the fore and back levellings was ±0.18 mm/√km.

The digital water crossing method with Zeiss DiNi12 was tested in 2004-2005 by measuring the loop T1-T3-T2-

T1, Figure 4. The observation procedure was as follows: the observer measured the nearest rod with a short, usually about 10 m sighting distance and then he pointed across the bay to another rod with 250-400 m sighting distance. Next, the observer moved to the opposite shore and the rods were also interchanged. The arrangement eliminated the zero point error of rod scales and the effect of collimation. Here we presupposed that the collimation of the DiNi12 did not change during the observations.

In the traditional water crossing (Kneissel, 1956), observations were always taken with two instruments simultaneously and reciprocally from both shores due to refraction. It was also presupposed that the refraction pattern was symmetric along the line of sight.

In Otsolahti, two observers worked side by side and the time frame between the reciprocal observations was in practice less than one hour. We used three Zeiss DiNi12 levels and a pair of three meter rods with 4 x scale. Air temperature was recorded at two elevations near the shoreline. Weather was cloudy and temperatures of ambient air and sea water were almost equal. The reflection of sun beams from the surface of water could disturb the operation of the digital level. The final height differences were obtained by multiplying the observed height readings with the corresponding scale factors (Table 1).

The interval T1-T4 and the loop T1-T3-T2-T1 were measured with the trigonometric levelling in July and November 2005.

Results

In Table 3 there are the results of the precise levelling (reference values), the digital water crossing and the trigonometric water crossing.

Table 3. *Results of the Otsolahti testfield measurements.*

Meas.	T1-T3 (mm)	T3-T2 (mm)	T2-T1 (mm)	T1-T4 (mm)	T1-T3-T2-T1 (mm)
Precise levelling 2004	+175,76	+114,86	-290,62	–	–
Precise levelling 2005	+175,60	+114,87	-290,47	+3829,73	–
Digital water crossing 2004	+175,1	+114,5	-290,1	–	-0,5
Digital water crossing 2005	+175,0	+114,5	-290,6	–	-1,1
Trigon. water crossing 2005	+175,6	+116,7	-291,2	+3830±5	+1,1

The errors of the digital as well of the trigonometric levelling were derived by comparing the observed height differences with the reference values (Figure 5).

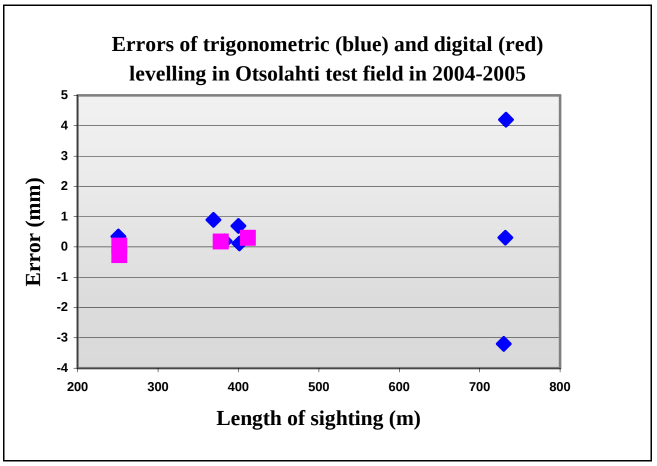

Fig. 5. *The accuracy of the water crossing measurements.*

Conclusions and future works

A special test field was established around the Otsolahti bay enabling the sightings of 260 m, 370 m, 405 m and 730 m. A bar code scale with four times magnification was constructed. As conclusion we can state that the digital levelling system Zeiss DiNi12 can be applied in the water crossing by magnifying each bar code element. The accuracy using the digital technique was approximately the same quality standard as the precise levelling (±1 mm/√km). According to the tests with the trigonometric water crossing method it is able to achieve better than ±5 mm/√km accuracy. In next future we will make 8-10 times enlargement of the bar code in order to examine even one kilometer water crossing using the Zeiss DiNi12 digital levelling technique.

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The Third Levelling of Finland

Mikko Takalo, **Pekka Lehmuskoski**, **Paavo Rouhiainen** and **Veikko Saaranen**
Finnish Geodetic Institute, Finland

The Third Levelling of Finland was carried out in 1978-2006. The network consists of 29 loops, 12 lines to mareographs, 8 joint lines to Sweden, 5 to Norway and 8 to Russia, in total 9060 km levelling lines. The main goals of the Third Levelling of Finland are the new height system of Finland, N2000 and the study of postglacial rebound. Eleven observers and 800 assisting persons have carried out the fieldwork. The achieved accuracy derived from the closing errors of the loops is ±0.85 mgpu/√km. The final results, i.e., the bench mark list, the technical description of the levelling and the theoretical description, will be published in the publications series of the Finnish Geodetic Institute.

UPS and DOWNS in the work by the Second Baltic Ring

Karsten Engsager
Danish National Space Center, Denmark

A short presentation of the results achieved and a more detailed description of techniques which have failed to be used in the adjustment of the Second Baltic Ring.

The Finnish Height Reference N2000

Veikko Saaranen, **Pekka Lehmuskoski**, **Paavo Rouhiainen** and **Mikko Takalo**
Finnish Geodetic Institute, Finland

The new height reference in Finland is N2000. It is computed in the NAP datum and in the zero tidal system. Heights are normal heights. This differs from the previous Finnish height datum N60, which has the zero point in Helsinki and the heights are orthometric heights.

National reference benchmark is located in Metsähovi. The starting value was derived from the NAP with Finnish version of the adjustment of levelling networks around the Baltic. Before the adjustment, all levellings were corrected to the epoch 2000.0 using the NKG2000LU model for the postglacial rebound. As a result of common uplift model, system epoch and weighting of observations the compatibility of our system with that of Swedish RH2000 is very good.

NKG Working Group for Geoid Determination, 2002-2006

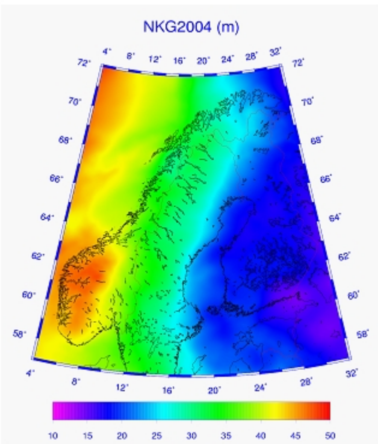
Dag Solheim
Norwegian Mapping Authority, Norway

NKG Working Group for Geoid Determination, 2002-2006

- NKG Activity
- National Activity
- Research Projects
- Fitting to GPS/levelling
- Quality Control
- Proposed Activities

NKG Activities

- New NKG2004 geoid
  - Presented at WG meeting in Copenhagen
  - Released Nov. 2004
  - Computed at DNSC by Rene Forsberg
- Joint NKG WG and OCTAS Study Course
  - Marine geoid, mean sea surface and oceanography
  - Arranged January 2005, Hurdalsjøen Hotel, Norway
  - Participants from Denmark, Norway, Poland and Sweden
  - Lecture notes available at http://www.octas.statkart.no/archive/octas_study_course_2005/



OCTAS/NKG WG Study Course

Lecture Notes:

- Dag Solheim, Introduction, (ppt) (pdf)
- Rene Forsberg, Physical Geodesy, Part 1, (ppt), (pdf)
- Rene Forsberg, Physical Geodesy, Part 2, Airborne Gravimetry, (ppt), (pdf)
- Rene Forsberg, Physical Geodesy, Part 3, ARCGICE, (ppt), (pdf)
- Ole B. Andersen, Satellite Altimetry, Part 1, (ppt), (pdf)
- Ole B. Andersen, Satellite Altimetry, Part 2, (ppt), (pdf)
- Ole B. Andersen, Satellite Altimetry, Part 3, (ppt), (pdf)
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- Ole B. Andersen, Satellite Altimetry, Part 5, (ppt), (pdf)
- Ole B. Andersen, Satellite Altimetry, Part 6, (ppt), (pdf)
- Philippa Berry, Satellite Altimetry, Retracking, (ppt), (pdf)
- Johnny Johannessen, Oceanography, Part 1, (ppt), (pdf)
- Frank Siegismund, Oceanography, Part 2, steric height, (ppt), (pdf)
- Jan Even Øie Nilsen, Oceanography, Part 3, (ppt), (pdf)
- Bente Lilja Bye, ESEAS, Part 1, (ppt), (pdf)
- Bente Lilja Bye, ESEAS, Part 2, (ppt), (pdf)

National Activities

- Baltic Countries
  - Visiting scientists at DNSC, close cooperation with RF/GS
  - Data exchange
  - Doctoral dissertations
- Denmark
  - DNSC
    - GOCINA, ARCGICE, IAG activities, Airborne Surveys and Geoid Computations, Computing Center for the NKG models etc etc
  - UoC

National Activities cont.

- Finland
  - FGI, Cooperation with Stuttgart University and Professor Ardalan, Tehran University, on methods for geoid calculation, tested with FGI data
- Norway
  - NMA/UMB, GOCINA, OCTAS, NN1954 Investigation
  - NTNU, Geoid computations, fit to GPS/levelling
  - UoB, Marine/Airborne surveys
- Sweden
  - KTH/LMV, Theoretical and numerical studies
  - 2 Doctoral dissertations

GOCINA and OCTAS

GOCINA, Geoid and Ocean Circulation In the North Atlantic, financed by EU

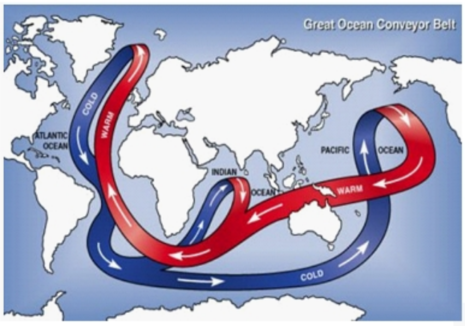
OCTAS, Ocean Circulation and Transport Between North Atlantic and the Arctic Sea, financed by the Norwegian Research Council

http://www.gocina.dk and

http://www.octas.statkart.no

NORWEGIAN MAPPING AUTHORITY

Global ocean Circulation Pattern

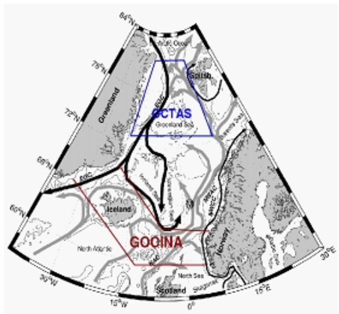


NORWEGIAN MAPPING AUTHORITY

Regional Ocean Circulation Pattern

NORWEGIAN MAPPING AUTHORITY

GOCINA & OCTAS Study Area



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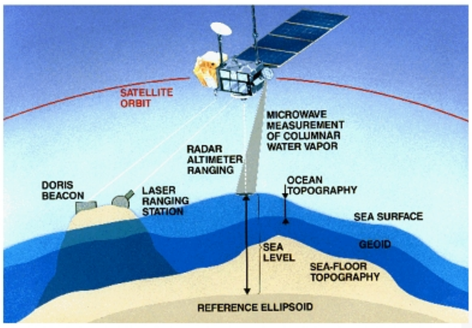
Interdisciplinary project



NORWEGIAN MAPPING AUTHORITY

Fundamental formula

MDT = MSS - Geoid

Residuals = MSS – Geoid - MDT

NORWEGIAN MAPPING AUTHORITY

GOCINA partners

DNSC, Danish National Space Center, DK

NMA, Norwegian Mapping Authority, NO

UEDIN, University of Edinburgh, UK

UREADES, University of Reading, UK

NERSC, Nansen Environmental and Remote Sensing Center, NO

CLS, Collecte Localisation Satellites, FR

NORWEGIAN MAPPING AUTHORITY

OCTAS partners

NMA, Norwegian Mapping Authority

UMB, University of Life Sciences (NLH, Ås)

NERSC, Nansen Environmental and Remote Sensing Center

NTNU, Department of Geomatics

UoB, University of Bergen

(UoO, University of Oslo)

External partners:

DNSC, Danish National Space Center

OSU, Ohio State University

UNR, University of Nevada Reno

NORWEGIAN MAPPING AUTHORITY

Project dissimilarities

GOCINA: Enhance existing knowledge, 3 year duration, 2002-2005

OCTAS: Establish new and enhance existing knowledge, 4 PhD students, originally 4 year duration, 2003-2006, now extended to 30.06.2007

NORWEGIAN MAPPING AUTHORITY

Why an airborne gravity campaign?

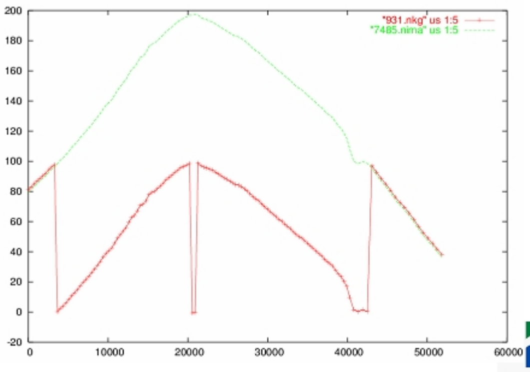
The airborne data are used to:

1) Assess and adjust existing marine gravity data and by this significantly improving their usability for geoid determination

2) Improving the gravity data coverage

NORWEGIAN MAPPING AUTHORITY

Marine data, error example



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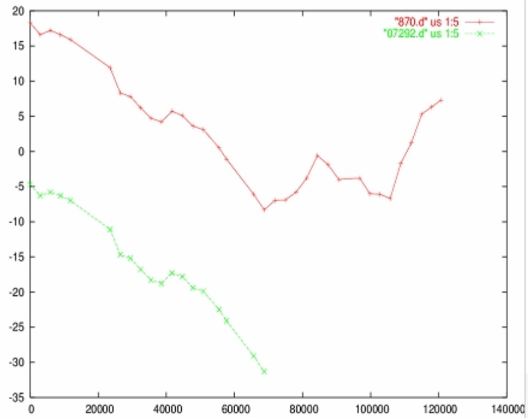

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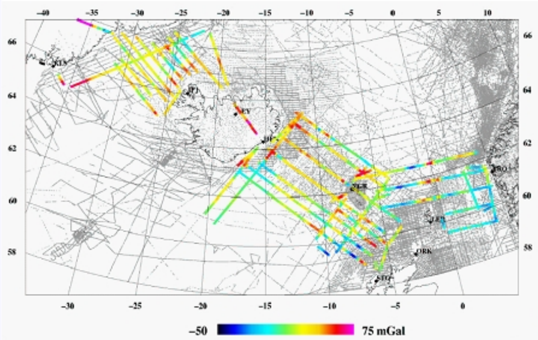
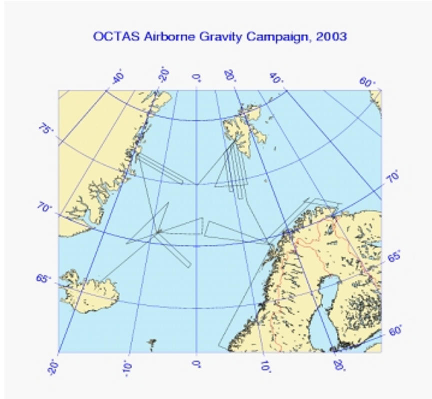
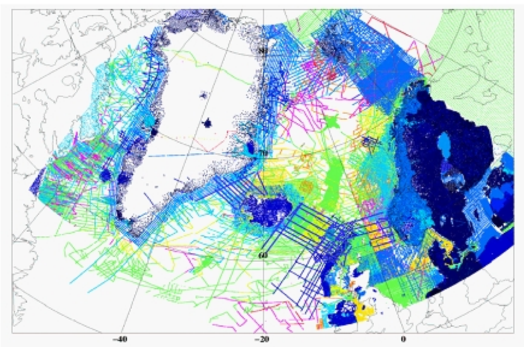
GOCINA Airborne Survey



NORWEGIAN MAPPING AUTHORITY



Gravity Coverage



Fundamental formula

MDT = MSS - Geoid

Residuals = MSS – Geoid - MDT

Usage of MDTs

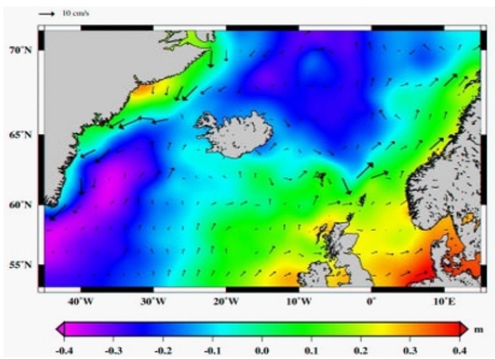
The derived MDTs will be used to:

Determine ocean circulation and transport

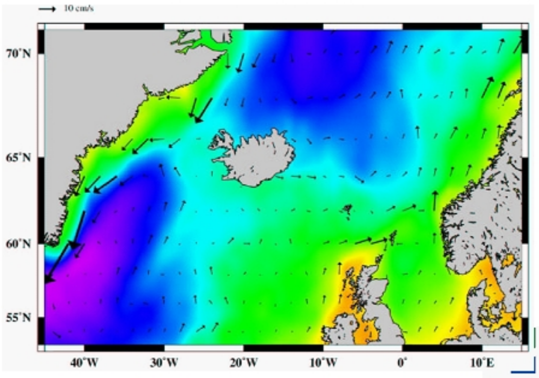
Included in ocean circulation and climate models

Improved accuracy of input data will lead to more reliable predictions and a better understanding of climate change

MDT from MSS - geoid



GOCINA MDT



NORWEGIAN MAPPING AUTHORITY

ARCGICE

Combination of Spaceborne, Airborne and In-Situ Gravity Measurements in Support of Arctic Sea-Ice Mapping

GOCINA/OCTAS spin off

Danish National Space Center, DK

Centre for Polar Observation and Modelling, Univ.College London, UK

Nansen Centre for Environmental Research, NO

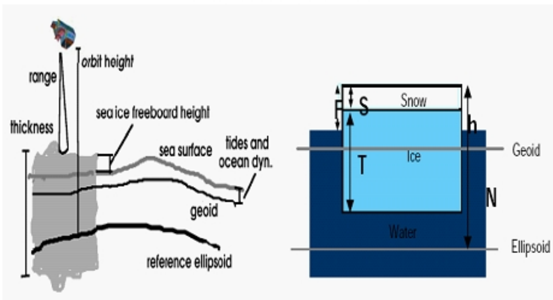
Niels Bohr Institute of Astronomy, Physics and Geophysics, DK

University of Copenhagen, Denmark, DK

Department of Geomatics Engineering, University of Calgary, CA

NORWEGIAN MAPPING AUTHORITY

Principles of Freeboard Determination

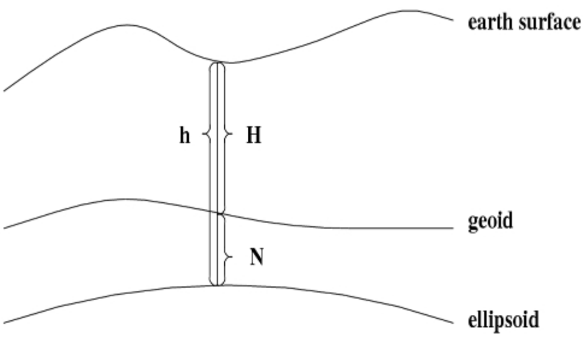


NORWEGIAN MAPPING AUTHORITY

Adjustment to GPS/levelling

- *Routinely done by most of the Baltic and Nordic countries*
- *Fitting procedure may vary some, Norway an iterative method*
- *Practical approach, what the users want*
- *Geoid/quasigeoid, orthometric/normal heights*

NORWEGIAN MAPPING AUTHORITY



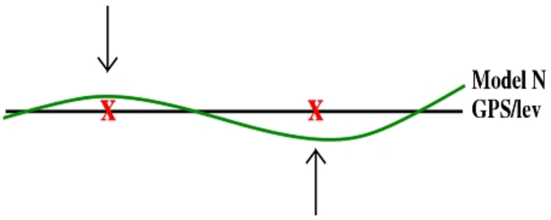
NORWEGIAN MAPPING AUTHORITY

How to fit your model to GPS/levelling data?

- Need a set of GPS/levelling data and a geoid/quasigeoid-model
- Compute the difference between the GPS/levelling data and your given model
- These differences are then used to compute a correction which when added to your original model gives you the fitted model

NORWEGIAN MAPPING AUTHORITY

Adjustment of the model



The points X shows where the model needs to be adjusted

NORWEGIAN MAPPING AUTHORITY

Norway, iterative approach

- *Models routinely being computed since the release of the NKG96 model*
- *Very limited amount of GPS/levelling data available at that time (1996)*
- *Areas already adjusted are in principle kept unchanged, only areas with new data (or where necessary due to blunders in earlier adjustment) are being modified*
- *Gradually improved models, high quality models were avaialble at an early stage*

NORWEGIAN MAPPING AUTHORITY

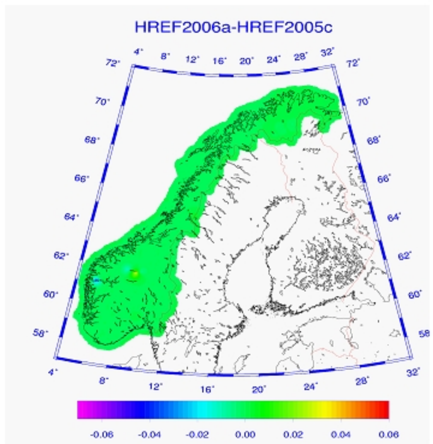
Norwegian models

HREF + GPS => Normal heights
(VREF + GPS => Orthometric heights)

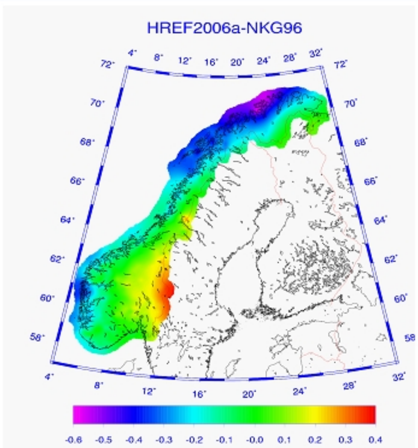
All models have been derived from the NKG96 quasigeoid

NKG96	**--->**	**NKG96n**
↓		↓
HREF1996		**VREF1996**
1998		**1998**
1999a,b		**1999a,b**
2000a,b,c		**2000a,b,c**
2001a,b,c		**2001a,b,c**
2002a,b,c,d,e		**2002a,b,c,d,e**
2003a,b,c,d,e,f		**2003a,b,c,d,e,f**
2004a,b,c,d,e		**2004a,b,c,d,e**
2005a,b,c		**2005a,b,c**
2006a,b		**2006a,b**

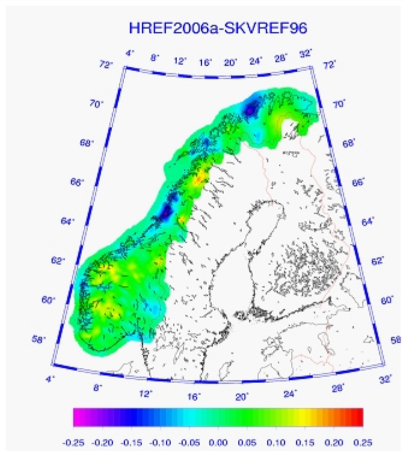
NORWEGIAN MAPPING AUTHORITY



NORWEGIAN MAPPING AUTHORITY



NORWEGIAN MAPPING AUTHORITY



NORWEGIAN MAPPING AUTHORITY

Quality Control

- Marine geoid: MSS-MDT
- Arctic: In situ sea ice thickness measurements combined with MSS, MDT
- Land areas: GPS/levelling
  - Accuracy of these independent geoid estimates
  - GPS vintage data
  - Are existing height systems suitable for proper quality control of the geoid?
- Progress?

NORWEGIAN MAPPING AUTHORITY

NKG geoid models

- NKG86, collocation
- NKG89, FFT, UTM
- NKG96, FFT, spherical multiband
- NKG2000, FFT, sph.
- NKG2002, FFT, sph., mod. kern.
- NKG2004, FFT, sph., mod. kern.

NORWEGIAN MAPPING AUTHORITY

GPS/lev SET	TORGEGPS	SWETGPS
No. of points	46	34
MODEL	Std.	Std.
NKG86	0.590	0.612
NKG89	0.101	0.117
NKG96	0.097	0.118
NKG2000	0.142	0.151
NKG2002	0.117	0.114
NKG2004	0.151	0.115

NORWEGIAN MAPPING AUTHORITY

GPS/lev SET	"NN1954"	"NN1994"
No. of points	240	240
MODEL	Std.	Std.
NKG86	0.299	0.275
NKG89	0.243	0.233
NKG96	0.160	0.092
NKG2000	0.185	0.106
NKG2002	0.134	0.066
NKG2004	0.138	0.076

NORWEGIAN MAPPING AUTHORITY

Quality Control Summary

- **Comparison with GPS/levelling data for the NKG2004 model gives quite similar results in Finland, Norway and Sweden. The std of the differences are typically on the order 5-7 cm**
- **Need high quality GPS and levelling data**

NORWEGIAN MAPPING AUTHORITY

Data availability

- Restrictions on distribution of gravity and digital elevation models
- Some suffer from lack of data
- NKG gravity database at DNSC (sw update), tremendous work done by CCT, RF and GS and their colleagues at DNSC
- Very time consuming to get access to data
- Need to solve this problem in order to really intercompare different methods for geoid computation

NORWEGIAN MAPPING AUTHORITY

WG activities, proposal

- Ensure that all WG members have sufficient access to relevant data
- Study the error propagation of the current theory and gravimetric data for NKG geoid modelling.
- Investigate the theory and methods being used, identify possible refinements and/or improvements and implement these.
- Collect and validate gravity data, both new and existing data
- Contribute to GOCE and other satellite gravimetric missions and make use of such data.
- Compute a gravimetric geoid and compare this model with geoid heights determined by GPS/levelling.
- Carry out an optimum combination of the gravimetric geoid and geoid heights determined by GPS/levelling, for the purpose of new height surface definition
- Compute a marine geoid for an optimal use of satellite altimetry in oceanography.

NORWEGIAN MAPPING AUTHORITY

Importance of the geoid

- Oceanography, ocean circulation and transport
- Monitoring of the Arctic, sea ice thickness determination
- Height determination by GPS

NORWEGIAN MAPPING AUTHORITY

Monitoring the Earth's System with the Global Geodetic Observing System (GGOS)

M. Rothacher
Department 1 "Geodesy and Remote Sensing"
GeoForschungsZentrum Potsdam, Germany

The helplessness we feel in view of natural disasters demonstrates very clearly that at present our knowledge of the Earth's complex system and our tools for the timely detection of potentially disastrous events are rather limited. Therefore, a deeper insight into the processes and interactions within this system is one of the most urgent challenges for our society. To continuously monitor changes in the Earth system and the processes causing natural disasters a global Earth observing system has to be established. The Global Geodetic Observing System (GGOS), that has been set up by the International Association of Geodesy (IAG), constitutes such an observing system concerning the contributions from geodesy. It represents an umbrella for the products derived by the IAG Services using the space geodetic techniques (VLBI, SLR/LLR, GNSS, DORIS), altimetry, InSAR, gravity missions, and in-situ measurements etc. and allows for the monitoring of the Earth system with an unprecedented accuracy of less than one part in one billion.

NGOS, The Nordic Geodetic Observing System

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Abstract

We describe the status and plans of the Nordic Geodetic Observing System (NGOS). NGOS integrates fundamental geodetic techniques for the long term observation of Earth system parameters that are important in the context of change in and on our planet. The Nordic Geodetic Commission (NKG) established a Task Force with the mission to prepare the plan and the practical implementation of the NGOS. NGOS is planned to be a regional implementation and densification of the Global Geodetic Observing System, GGOS. NGOS will contribute to the GGOS and other IAG Services; European activities such as EUREF, ECGN, EUVN, and ESEAS; provide the reference frames for the Nordic countries, as well as contribute to the global ones; support scientific projects related to the geodynamics of the Nordic area and provide ground-truth for satellite missions.

Background

Recent development on the global level has been very rapid. Most importantly, the fundamental role of geodesy as the provider of the global reference frame and observations of the Earth's shape, gravity field and rotation is currently acknowledged. Since 2004, IAG has participated in the preparation of the GEOSS (Global Earth Observation System of Systems) Implementation Plan. With the establishment of the Group on Earth Observations (GEO) in 2005, a more permanent mechanism on this has been possible. IAG was approved as a GEO Participating Organization. The regional system aligns with international efforts such as the Global Observing Systems and adheres to the Integrated Global Observing Strategy (IGOS). The efforts of GGOS lead also to the membership in the Integrated Global Observing Strategy Partnership (IGOS-P).

Over the last years, the European Commission and the European Space Agency have jointly proposed a programme for Global Monitoring for Environment and Security (GMES). The GMES represents a concerted effort to bring data and information providers together with users, so they can better understand each other and agree on how to make environmental and security-related information available to the people who need it.

A challenge for GMES is to gather relevant data and provide services, which will enable decision-makers to better anticipate or integrate crisis situations issues relating to the management of the environment and security.

The GMES is based on four inter-related components, namely services, observations from space, in-situ (including airborne) observations, and data integration and information management capacity. The range of services available by 2008 will be developed progressively. Services relies on the space and in-situ data providers. The data integration and information management will enable user access and the sharing of information.

In addition, access to socio-economic and other statistical data will be important. GMES is meant to be an open system that can easily accommodate new elements. The needs of GMES can be expected to be a major driver for the development of observation networks and applications in Europe and worldwide over the next decade and it will have a great impact also on geodesy and geodetic observing systems.

Current development means a unique opportunity for the geodetic community. Ignorance of the global development will be fatal for geodesy pushing it out from the mainstream of the development. Inside of the community we know that geodesy and geodetic methods will be an essential component in global monitoring.

There are two main contributions of geodesy to global monitoring,

(1) the maintenance of a highly accurate references frame as the backbone for all other observation systems, and
(2) observations of key variables of the Earth system, such as changes in its figure and gravity field, and variations in the Earth's rotation.

These quantities are related both to mass movements in the different parts of the Earth, from the inner core to the upper atmosphere, as well as the dynamics of the system.

The space-based technologies allow us now to determine positions in a globally coherent and highly accurate reference frame. Key variables of the Earth system such as the movements of the tectonic plates, land movement, Earth rotation, changes in the gravity field, and sea level changes are now observable in a globally consistent reference frame. There is an increasing demand for accurate and reliable geodetic observations for many scientific and non-scientific applications. However, the accuracy level achieved reveals inconsistencies between the global reference frame and the regional and national frames established for practical use.

GGOS will be geodesy‘s central interface to the scientific community and to society in general, and it will contribute to large international observation and science programs. Large parts of the physical observing network of the GGOS are already in place through the efforts of the national mapping authorities and other institutions involved in operational monitoring. The role of GGOS is to collect existing products, services, and act as a contact point to the outside world, promote techniques, and also coordinate that parameters, products and data are consistent with each other. GGOS must internally keep all its data, products and parameters on highest possible quality, independently of user needs, which sometimes may be quite modest. GGOS itself will not be the producer, but data and products are made in services (IAG or other sources). In this respect regional observing systems (e.g. NGOS) are in an essential role.

Demands for GGOS are quite challenging. One has to find stabilization of global geodetic infrastructure on political level to ensure a stable GGOS for 30+ years. At the same time development of observing techniques require unification on the level of 10^{-9} in g and reference frames. Currently, IAG activities are based on voluntarily participation of various authorities and institutions. There are already threats to close national facilities, and there is no guarantee that existing infrastructures will be preserved. An ultimate goal is to achieve a high-level political intergovernmental agreement, possibly under UN science programs to guarantee the continuation of geodetic networks on National level. Such an agreement, however, is not yet in view.

Definitions and principles of NGOS should follow those of GGOS as closely as possible. The concern on the political decisions are common, and downgrading National facilities are not in hands of the scientific community. Therefore, even in the Nordic area, a high-level intergovernmental agreement and commitment on the national level is the most preferable to guarantee the continuation of the Nordic geodetic frames, infrastructure and facilities.

The vision and mission of GGOS (http://www.ggos.org) can serve also as a general guideline for the planning of the NGOS. The vision of GGOS is as follows:

- GGOS integrates different techniques, different models and different approaches in order to achieve a better consistency, long-term reliability and understanding of geodetic, geodynamic and global change processes.
- GGOS provides the scientific and infrastructure basis for all global change research in Earth sciences.
- In the frame of GGOS, the Earth system is viewed as a whole by including the solid Earth as well as the fluid components, the static and time-varying gravity field in its products.
- GGOS is geodesy’s contribution (products and discoveries) to Earth sciences and the bridge to the other disciplines; it asserts the position of geodesy in geosciences.
- GGOS integrates the work of IAG and emphasizes the complementarity of the broad spectrum of geodetic research and application fields.

The mission of GGOS is:

- to collect, archive and ensure the accessibility of geodetic observations and models;
- to ensure the robustness of the three fundamental fields of geodesy, namely geometry and kinematics,
- Earth orientation and rotation, and gravity field and its variability;
- to identify a consistent set of geodetic products and to establish the requirements concerning the products‘ accuracy, time resolution, and consistency;
- to identify IAG service gaps and develop strategies to close them;
- to stimulate close cooperation between existing and new IAG services;
- to promote and improve the visibility of the scientific research in geodesy;
- to achieve maximum benefit for the scientific community and society in general.

NGOS aims to provide geodetic observations for the Nordic area that are of sufficient quantity and quality to serve most of the needs of global Earth observation as well as practical and scientific applications in the region. For the Nordic countries, a main focus will be on crustal motion, dynamics of glaciated areas and sea level. In particular, NGOS

- will contribute to the GGOS and other IAG Services
- will contribute to global Earth observation systems,
- will contribute to European activities such as EUREF, ECGN, EUVN, and ESEAS,
- will coordinate the work on the reference frames for the Nordic countries, and the region as well as contribute to the global ones,
- will support scientific projects related to the geodynamics of the Nordic area,
- will provide ground-truth for satellite missions.

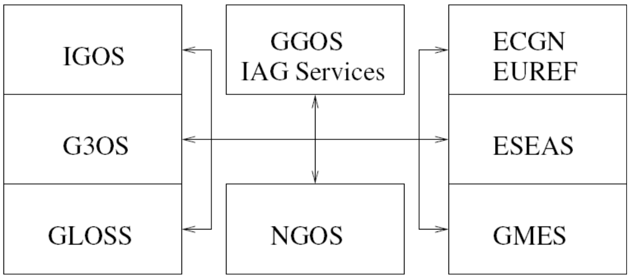

Figure 1. *Relations of NGOS to other activities.*
ECGN: European Combined Geodetic Network;
ESEAS: European Sea-Level Service;
EUREF: Reference frame subcommission for Europe;
G3OS: Global Observing Systems;
GGOS: Global Geodetic Observing System;
GMES: Global Monitoring for Environment and Security
IAG: International Association of Geodesy;
IGOS: Integrated Global Observing Strategy;
NGOS: Nordic Geodetic Observing System.

NGOS is envisaged to provide the necessary observations to determine

- geodetic positions and to infer the kinematics of the Earth surface,
- gravity and its temporal changes, and
- Earth orientation parameters, i.e. precession, nutation, length of day, and polar motion.

Plans of the NGOS were published in Poutanen *et al.*, (2006, 2005a,b) based on the work of the Task Force. In this document we summarise the structure and plans of the NGOS, make an inventory of existing infrastructure, and make a proposal for the NKG for the future tasks to implement the NGOS on the practical level and ensure its compatibility to the GGOS project.

Proposed structure of NGOS

The geographic extent of NGOS is currently defined as the Nordic region, including Iceland, Greenland and Svalbard. It is recommended that the geographical region is extended to include also the area of Baltic States. This covers the area of the ice-covered part of the Northern Europe during the last ice age, and therefore of the common geophysical interest.

Only the ground components of the geodetic observation techniques and infrastructures are considered in NGOS. Densifications, e.g. in special target areas such as glaciers, tectonically active structures, or near tide gauges, can be accomplished using remote sensing techniques, such as space and airborne radar and laser systems. Sea level can be monitored using satellite altimetry. The large scales of the gravity field and its changes are studied using observations of the motions of satellites by SLR and GPS or by dedicated gravity satellite missions.

In the next chapter we will discuss on the current existing infrastructure. In Table I, extracted from the original NGOS plan we have summarised the proposed techniques considered in NGOS. Geodetic VLBI and SLR are only on a few stations in the area, but they form the most fundamental part of the network. They cannot be replaced with any other techniques, and due to their nature, they are the most vulnerable components if budget cuts or national network downgrades are made. Doris stations are controlled by CNES, and there are only two Doris station in the NGOS area. GNSS technique has a lot of redundancy, receivers are relatively cheap and maintaining of a permanent reference network is simple. Spatial coverage of the GNSS network is good.

Concerning spatial variations of gravity and its temporal changes, we propose concentration on the use of modern, absolute gravimeters as expressed in NGOS/Absolute Gravimetry plan (Scherneck et al., 2002) and "Draft plan for absolute gravity campaigns in the Fennoscandian land uplift area" by Mäkinen (2003). The absolute gravity measurements in the Nordic area is made as a co-operation of Danish National Space Center, The Finnish Geodetic Institute, Norwegian Mapping Authority, National Land Survey of Sweden, Onsala Space Observatory (Sweden), Norwegian University of Life Sciences in Aas, University of Hannover (Germany), and Federal Agency for Cartography and Geodesy (BKG, Germany). Relative and especially superconducting gravimetry are an important part of the gravity net. Temporal variation can be tracked with a superconducting gravimeter, the number of which is only 3 in the area.

We also emphasize the importance of geoid determination. By nature, it is not limited to the NGOS stations or NGOS plan. In the future, the new gravity satellite missions, especially GRACE and GOCE will give their contribution also to the Nordic geoid models.

Levelling as a traditional technique is slow and expensive but accurate, and in some circumstances cannot be replaced by any other method. National levelling networks exist with a number of repeated nationwide precise levellings. More national levelling projects, however, seems quite unlikely in the future.

Tide gauges are mostly out of the control of the geodetic community, because they are maintained by other authorities. Tide gauges are essential in study of global change, and one should assure access to the tide gauge data, either via PSML, ESEAS or by (bilateral) agreements with authorities owning the tide gauges.

Current existing infrastructure

NKG has tried to act as a platform for sharing the knowledge concerning construction of various geodetic networks and in co-operation of geodetic campaigns. However, at the end it has always been the responsibility of an individual country or a research team to implement the work in practice. The Nordic countries have historically been building up their geodetic networks quite independently. There has been only a limited amount of co-operation between the countries or techniques. Inside the countries even collaboration between organizations has not been optimal. Tide gauges are typical examples, because institutions taking care of them are generally outside of the geodetic community.

Table 1. Summary of techniques considered in NGOS.

Technique	Objective	Accuracy	Component(s)
VLBI	Point positioning relative to the network of quasars	0.001 ppb 0.1 mas	Surface displacement; Earth rotation; Reference frame orientation
SLR	Point positioning relative to satellites	< 1 cm (range) 1-2 cm	Surface displacement; Earth rotation; Reference frame origin
GNSS	Point positioning relative to a satellite system	E: 1-2 cm [*)] C: 1-2 mm	Surface displacement; Reference frames, densification
DORIS	Point positioning relative to satellites	1-5 cm	Surface displacement; Reference frame
Levelling	Height differences of points relative to the geoid	< 1 mm/km^{½}	Surface displacement; Height differences
Tide gauges	Height of points relative to sea level	E: 10 cm C: 1 cm	Surface displacement; Sea level variation
Absolute gravimeters	Absolute gravimetric accelerations	2-3 µGal	Surface displacement; Earth rotation; Gravity; Reference frame
Superconducting gravimeters	Relative gravimetric accelerations	0.1 µGal (< 1 nGal periods)	Surface displacement; Earth rotation; Gravity; Reference frame
Spring gravimeters	Relative gravimetric accelerations	2-3 µGal	Gravity; Reference frame
[*)] *E means episodical and C continuous measurements*			

In each country there are networks of permanent GNSS stations which partly are operated by the national geodetic authorities. The co-ordination concerning e.g. location, construction, facilities and products was not optimal when the stations were built. This means e.g. that the stations have different monumentation, have different types of equipment, produce slightly different products and possibly are not optimally spread over the Nordic Area. However, the basic observables are the same at all stations, thus allowing e.g. the common Nordic computation of the EPN block, or the collaboration in the projects like BIFROST. Another form of collaboration exists between Denmark, Norway and Sweden since the year 2000, concerning exchange of data and various products for navigation and real-time application purposes.

The Finnish Geodetic Institute has been active in absolute gravimetry and has been performing measurements on stations over the Nordic Area for many years. Groups from USA and Germany have also made absolute gravity measurements in the Nordic Area. The current NGOS AG plan clearly demonstrates the current co-operation in this field. Since 2003, also Norwegian University of Life Sciences in Aas has an absolute gravimeter, and the National Land Survey of Sweden has purchased an absolute gravimeter in 2006, which are substantial increase in the resources. Most of the measurements in Finland and Sweden have been performed at stations with other geodetic techniques, such as permanent GNSS stations and/or tide gauges.

There is a superconducting gravimeter at Metsähovi and Ny-Ålesund. These two stations and additionally Onsala, are also equipped with a geodetic VLBI. These three stations are internationally important fundamental resources since several specific techniques are collocated to these stations. Metsähovi has additionally collocated other two space geodetic equipment, namely the SLR and DORIS. Since 1978 Metsähovi has participated the SLR programme, and is currently the Northernmost SLR station. Stations in geodetic VLBI and SLR contributes to the work of IVS and ILRS which are the IAG services.

GNSS data of some Nordic stations are used in IGS, but a more wide selection of Nordic GNSS stations belong to the EPN, the European Permanent GPS Network, coordinated by EUREF. EUREF has during the last decade become active concerning European co-operation and examples of this are:

- the European reference frame ETRS89
- the European Network of permanent GNSS stations EPN
- the European vertical network EUVN
- the European height network UELN and the height system EVRS 2000
- ECGN

The Nordic countries have adopted national ETRS89-realisations as their national reference systems. NKG is responsible for one of the EPN analysis centres and the responsible organization is currently National Land Survey in Sweden. NKG has urged the countries for Nordic co-operation concerning the Nordic height systems. The joint Nordic adjustment of the levelling networks is headed towards the common vertical datum in the area. NGOS is in line with these initiatives towards Nordic co-operation concerning the national geodetic networks and geodetic stations.

Table 2. Components and associated services

Components	IAG service(s)	Other service(s)
Surface displacement	IVS, ILRS, IGS, TIGA, WEGENER	PSMSL, ESEAS
Earth rotation	IERS	
Gravity	BGI, IGeS, ICET	
Reference frame	EUREF, IERS	

Table 3. Infrastructure and data

Technique	**Stations**	**Responsible institutes**[1]	**Data archive / availability**
VLBI	Metsähovi, Onsala, Ny Alesund	FGI, OSO, SK	IVS / free availability of results
SLR	Metsähovi (+ Riga)	FGI	ILRS / free availability of results
GNSS	many (permanent), episodic	FGI, LM, OSO, SK, KMS, DNSC	EPN, OSO, National authorities / partly free (EPN), partly restricted
DORIS	Metsähovi, Ny Alesund	FGI, SK	IDS, CNES / free
Levelling	National levelling networks	FGI, LM, SK, KMS, DNSC	Nordic Data Bank and UELN / restricted availability
Tide gauges	many	SMHI, FIMR, SK, DMI	PSML, national authorities / free (PSML), restricted, commercial
Absolute gravimeters	two instruments, many points, episodic	FGI, UMB	no joint data bank / restricted
Superconducting gravimeters	Metsähovi, Ny Alesund	FGI, NMA	GGP / for members free
Spring gravimeters	many, national networks	FGI, LM, SK, KMS, GTK	national data banks / restricted

[1]**Abbreviation of institutes:**

DMI	Danish Meteorological Institute
DNSC	The Danish National Space Center
FGI	Finnish Geodetic Institute
FIMR	Finnish Institute of Marine Research
GTK	Geological Survey of Finland
KMS	National Survey and Cadastre of Denmark
LM	National Land Survey of Sweden
OSO	Onsala Space Observatory
SK	Norwegian Mapping Authority
SMHI	Swedish Meteorological and Hydrological Institute
UMB	Norwegian University of Life Sciences

Table 4. The NGOS Network

Site name	Coordinates			Techniques							Local		Committed to							
	φ	λ	h(m)	VLB	SLR	GNS	DO	AG	SCG	TG	CN	FP	ITR	IVS	IGS	ILR	ECG	EPN	GGP	ESE
Metsähovi	60.218	24.395	95	C	C	C	C	R	C	:	R	:	C	C	C	C	C	C	C	:
Ny-Alesund	78.930	11.865	78	C	:	C	C	R	C	C	R	R	C	C	C	:	C		C	C
Onsala	57.395	11.926	47	C	:	C	:	R	:	:	R	:	C	C	C	:	C	C	:	:
Riga	56.949	24.059	35	:	C	C	:	R	:	:	:	:	C	:	:	C	:	:	:	:
Trysil	61.423	12.382	730	E	P	C	:	R	P	:	R	:	:	:	:	:	:	:	:	:
Alesund	62.476	6.199	190	:	:	C	:	R	:	C	:	:	:	:	:	:	:	:	:	C
Andoya	69.278	16.009	411	:	:	C	:	:	:	C	:	:	:	:	C	:	:	:	:	C
Arjeplog	66.318	18.125	489	:	:	C	:	R	:	:	E	:	:	:	:	:	:	:	:	:
Bergen	60.289	5.267	94	:	:	C	:	P	:	C	:	:	:	:	:	:	:	:	:	C
Bodo	67.275	14.358	51	:	:	C	:	P	:	C	:	:	:	:	:	:	:	C	:	C
Borås	57.715	12.891	220	:	:	C	:	R	:	:	E	:	:	:	C	:	:	C	:	:
Buddinge	55.739	12.500	:	:	:	C	:	:	:	:	E	E	:	:	:	:	:	C	:	:
Copenhagen	55.7	12.5	:	:	:	:	:	R	:	C	:	:	:	:	:	:	:	:	:	:
Degerby	60.032	20.385	20	:	:	E	:	:	:	C	P	:	:	:	:	:	:	:	:	:
Dombås	62.073	9.114	733	:	:	C	:	:	:	:	:	:	:	:	:	:	:	:	:	:

Site name	Coordinates			Techniques							Local		Committed to							
	φ	λ	*h*(m)	VLB	SLR	GNS	DO	AG	SCG	TG	CN	FP	ITR	IVS	IGS	ILR	ECG	EPN	GGP	ESE
Furuögrund	64.879	21.048	:	:	:	:	:	:	:	C	:	:	:	:	:	:	:	:	:	:
Göteborg	57.687	11.981	:	:	:	:	:	R	:	:	E	:	:	:	:	:	:	:	:	:
Hässleholm	56.092	13.718	114	:	:	C	:	:	:	:	E	:	:	:	:	:	:	:	:	:
Helsingør	56.045	12.580	:	:	:	:	:	R	:	:	:	:	:	:	:	:	:	:	:	:
Höfn	64.267	-15.198	:	E	:	C	:	E	:	:	E	:	C	:	C	:	C	C	:	:
Honefoss	60.144	10.249	181	:	:	C	:	:	:	:	:	:	:	:	:	:	:	:	:	:
Irbene	57.888	21.852	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
Joensuu	62.391	30.096	114	:	:	C	:	R	:	:	R	:	C	:	:	:	:	C	:	:
Jönköping	57.745	14.060	260	:	:	C	:	:	:	:	E	:	:	:	:	:	:	:	:	:
Karlstad	59.444	13.506	114	:	:	C	:	:	:	:	E	:	:	:	:	:	:	:	:	:
Kevo	69.756	27.007	:	:	:	C	:	P	:	:	R	:	:	:	:	:	:	:	:	:
Kiruna	67.878	21.060	498	:	:	C	:	R	:	:	E	:	C	:	C	:	:	C	:	:
Kivetty	62.820	25.702	:	:	:	C	:	:	:	:	R	R	:	:	:	:	:	:	:	:
Klaipeda	55.723	21.178	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
Kramfors	62.855	18.096	57	:	:	C	:	R	:	:	:	:	:	:	:	:	:	:	:	:
Kristiansand	58.083	7.907	148	:	:	C	:	:	:	C	:	:	:	:	:	:	:	:	:	C
Kuressaare	58.250	22.487	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
Kuusamo	65.910	29.033	:	:	:	C	:	:	:	:	R	:	:	:	:	:	:	:	:	:
Leksand	60.722	14.877	478	:	:	C	:	:	:	:	E	:	:	:	:	:	:	:	:	:
Lovö	59.338	17.829	80	:	:	C	:	:	:	:	E	:	:	:	:	:	:	:	:	:
Mårtsbo	60.595	17.259	75	:	:	C	:	R	:	:	E	:	C	:	C	:	C	C	:	:
Norrköping	58.590	16.246	41	:	:	C	:	:	:	:	E	:	:	:	:	:	:	:	:	:
Olkiluoto	61.240	21.473	:	:	:	C	:	P	:	:	R	R	:	:	:	:	:	:	:	:
Oskarshamn	57.066	15.997	150	:	:	C	:	:	:	:	E	:	:	:	:	:	:	:	:	:
Oslo	59.737	10.368	221	:	:	C	:	:	:	C	:	:	:	:	:	:	:	:	:	C
Östersund	63.443	14.858	490	:	:	C	:	R	:	:	E	:	:	:	:	:	:	:	:	:
Oulu	65.086	25.893	:	:	:	C	:	P	:	:	R	:	:	:	:	:	:	:	:	:
Överkalix	66.318	22.773	223	:	:	C	:	:	:	:	E	:	:	:	:	:	:	:	:	:
Panevezys	55.375	24.360	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
Pope	57.403	21.857	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
Qaqortoq	60.715	313.952	:	:	:	C	:	P	:	C	E	:	:	:	C	:	C	C	:	:
Reykjavik	64.139	-21.955	:	:	:	C	C	R	:	C	R	:	C	:	C	:	C	C	:	C
Romuvaara	64.217	29.931	:	:	:	C	:	:	:	:	R	R	:	:	:	:	:	:	:	:
Skellefteå	64.879	21.048	81	:	:	C	:	R	:	:	E	:	:	:	:	:	:	C	:	:
Smidstrup	55.641	9.559	:	:	:	C	:	P	:	:	E	E	:	:	:	:	C	C	:	:
Smögen	58.353	11.218	45	:	:	C	:	R	:	C	P	:	C	:	:	:	:	:	:	:
Sodankylä	67.421	26.389	300	:	:	C	:	R	:	:	R	:	:	:	:	:	:	C	:	C
Stavanger	59.018	5.599	105	:	:	C	:	R	:	C	:	:	:	:	:	:	:	:	:	:
Suldrup	56.842	9.742	:	:	:	C	:	P	:	:	E	E	:	:	:	:	C	C	:	:
Sundsvall	62.232	17.660	32	:	:	C	:	:	:	:	E	:	:	:	:	:	:	:	:	:
Suurupi	59.467	24.383	:	:	:	C	:	E	:	:	E	:	:	:	:	:	:	:	:	:
Sveg	62.017	14.700	491	:	:	C	:	:	:	:	E	:	:	:	:	:	:	:	:	:
Tebstrup	55.968	9.881	:	:	:	:	:	R	:	:	:	:	:	:	:	:	:	:	:	:
Toravere	58.267	26.467	:	:	:	P	:	P	:	:	:	:	:	:	:	:	:	:	:	:
Tromsø	69.663	18.938	132	E	E	C	:	E	:	C	:	:	:	:	C	:	:	C	:	C
Trondheim	63.371	10.319	318	:	:	C	:	R	:	C	:	:	:	:	:	:	:	C	:	C
Trygde	58.006	7.555	48	:	:	C	:	:	:	C	:	:	:	:	C	:	:	:	:	C
Tuorla	60.416	22.443	:	:	:	C	:	P	:	:	R	:	:	:	:	:	:	:	:	:
Umeå	63.578	19.510	54	:	:	C	:	:	:	:	E	:	:	:	:	:	:	:	:	:
Uppsala	59.865	17.590	57	:	:	C	:	:	:	:	:	:	:	:	:	:	:	:	:	:
Vaasa_GPS	62.961	21.771	58	:	:	C	:	R	:	:	R	:	C	:	:	:	:	C	:	:
Vaasa_AA	63.085	21.646	:	:	:	:	:	R	:	:	:	:	:	:	:	:	:	:	:	:
Vänersborg	58.693	12.035	170	:	:	C	:	:	:	C	:	:	:	:	:	:	:	C	:	C
Vardø	70.336	31.031	175	:	:	C	:	:	:	:	:	:	:	:	:	:	:	:	:	:
Vilhelmina	64.698	16.560	450	:	:	C	:	:	:	:	E	:	C	:	:	:	:	:	:	:
Vilnius	54.722	25.338	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
Virolahti	60.539	27.555	:	:	:	C	:	E	:	:	R	:	:	:	:	:	:	:	:	:
Visby	57.654	18.367	80	:	:	C	:	R	:	C	E	:	C	:	C	:	:	C	:	:
Viski	56.067	26.767	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:

Columns: φ = approximate latitude; λ = approximate longitude, *h* = ellipsoidal height; VLB = VLBI; SLR = SLR; GNS = GNSS (GPS + GLONASS); DO = DORIS, AG = Absolute gravimeter, SCG = Superconducting gravimeter; TG = Tide gauge; CN = Control network, FP = Footprint; ITR = ITRF point; IVS = IVS point; IGS = IGS point; ILR = ILRS point; ECG = ECGN point; EPN = EPN point; GGP = GGP point; ESE = ESEAS point

Symbols: P = proposed / planned; M = monument available; E = episodic measurements; R = repeated measurements; C = continuous measurements; : = none

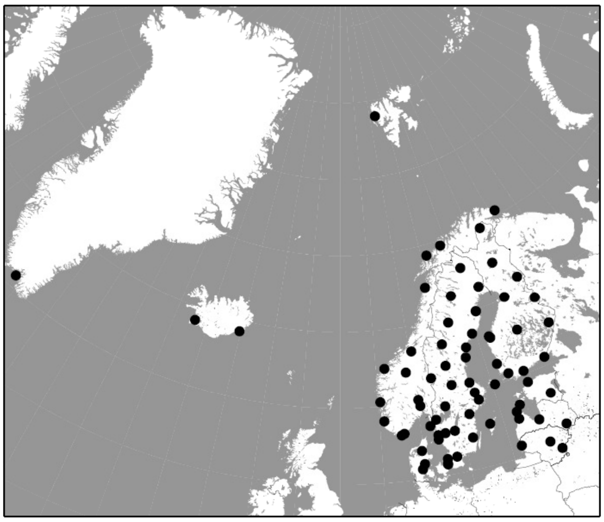

Figure 2. *The geographical area covered by the NGOS and proposed NGOS stations.*

Future of the NGOS

NGOS will be one of the key issues of the NKG in coming years. Most of the observational infrastructure is in place. However, it the responsibility of the individual institutions to maintain the instrumentation, infrastructure and networks. Stability is the key issue. There is no common mechanism to guarantee the continuation of the individual parts of the NGOS over next decades. Political or economical changes may be hazardous, and the rest of the community can do very little if some parts are decided to decease nationally.

Data infrastructure of NGOS is more unorganised than the network itself. There are no common data archives, nor there are any common data policy how the data are accessed. Some data are free, some partly free and many have restrictions. Obviously it would be the first task for the NGOS to establish a meta data base for existing data, archives and a common mechanism for access. With some exceptions, most data are available but standardisation and recommendations for access and use are needed. However, there is the question who will do the actual work, how the access, copyrights, and so on will be arranged.

NGOS should follow as closely as possibly the development of GGOS. NGOS should be a regional implementation and extension of GGOS. Therefore, it would be important that a member of NGOS core group is in the GGOS steering committee. Currently Markku Poutanen is as a representative of the IAG Commission 3 in GGOS Steering Committee. Previous member of the NGOS group, Hans-Peter Plag is a vice president of the GGOS.

NGOS will not replace NKG working groups. It is a coordinator and a joint forum for the work done in the Working Groups. The NGOS Steering Committee (SC) should contain representatives from each country, but most importantly, all Working Group chairpersons should be members of the SC. Also, a representative of the NKG Presidium should be in the NGOS SC.

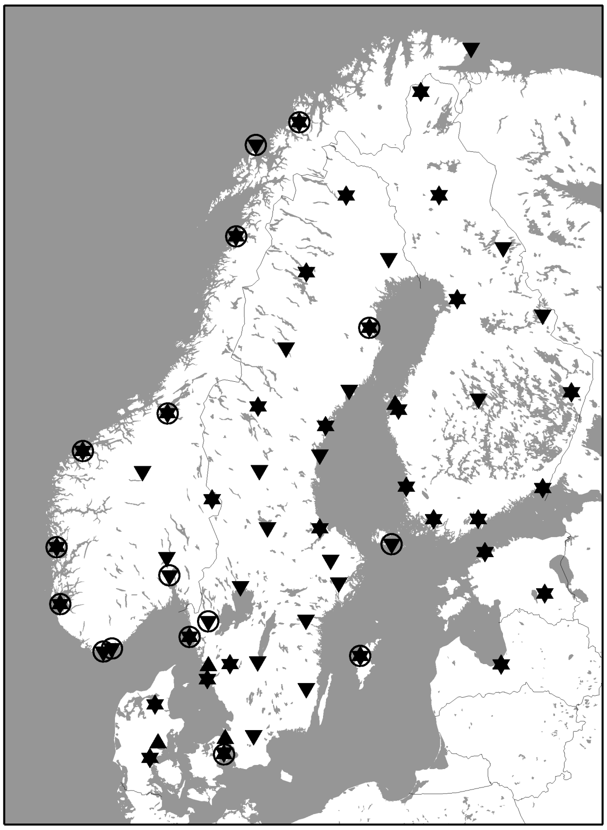

Figure 3. *NGOS plan. Absolute gravity points (triangles), Nordic permanent GPS network (upside down triangles) and tide gauges (circles). All absolute gravity points are occupied with a GNSS instrument.*

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Poutanen M., P. Knudsen, M. Lilje, T. Nørbech, H.- P. Plag, H.-G. Scherneck, (2005a). NGOS. Report of the Nordic Geodetic Commission Task Force. http://www.nkg.fi /nggos. html. 30 pages.

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Appendix. Meetings of the NGOS Task Force 2003-2006.

Copenhagen, 21.-22.8.2003
Masala, 30.9-1.10.2003
Onsala, 19.-20.2.2004
Göteborg, 28.-29.3.2006

Activities of the Summer Institute for Historical Geophysics, Åland

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1. The character of the institute

The Summer Institute for Historical Geophysics, located in the Åland Islands, started its activities in 1993. It is the author's one-man-institute, performing research, issuing publications, giving lectures and now and then undertaking special commissions, within the field of historical geophysics. The author can be said to function as a combined director, scientist and secretary of the institute.

Originally, the institute mostly operated during summers, but nowadays it operates also in spring and autumn. (During winter the author is more occupied with giving lectures in nautical geophysics at the Åland Maritime Institute.) The institute normally works in a small house in the village of Haraldsby, some 500 m from the Baltic Sea. In summers, however, the institute occasionally works in a small cottage in the village of Bomarsund, only some 10 m from the Baltic Sea, and 100 m from the world's oldest preserved sea level gauge. Weather permitting, the institute's scientist likes working outdoors on a suitable rock somewhere along the shore, with a beautiful view over the sea with its bays and islands.

2. Research and publications

The scientific research of the institute deals with historical geophysical data and their use in geophysics as well as history. Emphasis is on the Nordic countries and the Baltic Sea area. Geophysically, the research is concerned with positioning, gravity, postglacial rebound, tides, sea level changes, and climate changes. Historically, it is concerned with the times from the Vikings up till today, with a concentration on the last three centuries. A considerable work has been carried out on the world's longest sea level series, that of Stockholm commencing in 1774, and its relation to climate changes (see appendix for main results). Inspiring cooperation has, in certain fields, taken place with other scientists: Jaakko Mäkinen, Finnish Geodetic Institute; Hans-Georg Scherneck, Onsala Space Observatory; Hans Bergström, Earth Sciences Department at the Uppsala University.

Most of the research is published in the series "Small Publications in Historical Geophysics", issued by the institute. Hitherto 14 such publications have been issued; see the list below. Separate copies of these publications can be obtained free of charge. There is also a book containing the first 12 publications in a composite volume. This can be obtained against payment.

3. Lectures and special commissions

The institute, or rather its scientist, occasionally gives lectures within its field. Such lectures have been given primarily to geoscientific state authorities – geodetic, geological, oceanographic and meteorological – mostly in Sweden but also in other Nordic countries. Some more regular lectures have been given at the Åland Maritime Institute. The most frequent subjects have been old and modern reference systems, postglacial rebound and old shore lines, and Baltic Sea level and winter climate changes.

Now and then the institute's scientist also undertakes special commissions for which he might have special competence. Typical examples illustrating the variety of such commissions are the following works:

- Investigating old reference systems for a Gulf of Bothnia society of marine archeology searching for a sunken ship.
- Explaining the historical and future motion of the Arctic circle for the Swedish Rail Administration putting up an information board for tourists.
- Calculating old shore levels for the Uppsala University, private societies etc. for historical purposes.
- Acting specialist for the Government of Åland and the Ministry of Justice in Finland concerning the definition of the maritime borders of Åland according to international law.
- Giving scientific advice to the Royal Court of Sweden concerning His Majesty's map collection.

Small Publications in Historical Geophysics (1995 – 2005)

1. Ekman, M: Postglacial uplift of the Åland Islands, and the world's oldest preserved sea level gauge. 1995.

2. Ekman, M: Extreme annual means in the Baltic Sea level during 200 years. 1996.

3. Ekman, M: Anomalous winter climate coupled to extreme annual means in the Baltic Sea level during the last 200 years. 1997.

4. Ekman, M, & Mäkinen, J: An analysis of the first gravimetric investigations of the Earth's flattening and interior using Clairaut's theorem. 1998.

5. Ekman, M: Long-term changes of interannual sea level variability in the Baltic Sea and related changes of winter climate. 1998.

6. Scherneck, H-G, & Ekman, M: Analysis of tidal observations in the Arctic Ocean made during the Vega expedition. 1999.

7. Ekman, M: Determination of global sea level rise and its change with time. 2000.

8. Ekman, M: Computation of historical shore levels in Fennoscandia due to postglacial rebound. 2001.

9. Ekman, M: An investigation of the tidal conditions at the loss of the world's most impressive sailing ship. 2002.

10. Ekman, M: The visibility of the midwinter sun at the first Viking settlement in America – calculations compared with the Icelandic sagas. 2002.

11. Bergström, H, & Ekman, M: A period of anomalous winter climate and the Scandinavian glacier maximum in the 1700s. 2002.

12. Ekman, M: The world's longest sea level series and a winter oscillation index for northern Europe 1774 – 2000. 2003.

13. Ekman, M: A royal Swedish-Norwegian Viking fleet conflict studied by postglacial rebound and other calculations. 2004.

14. Ekman, M: Changes in winter climate variability deduced from the Baltic Sea level, and the winter that never arrived. 2005.

Appendix: Summary of main results from the world's longest sea level series, Stockholm 1774 – 2000

The apparent postglacial land uplift, i.e. the uplift relative to the sea level, is 4.9 ± 0.2 mm/yr for the first half of the time period and 3.9 ± 0.2 mm/yr for the second half, yielding an increased climatic sea level rise of 1.0 ± 0.3 mm/yr from the 1800s to the 1900s.

The absolute land uplift at Baltic Sea mareographs, estimated from geophysical models of the postglacial rebound, compared with the apparent land uplift there has given a climatic sea level rise during the last century of 1.0 ± 0.2 mm/yr. Combining this with the result above, the sea level rise during the century before the last one is shown to be 0.0 ± 0.4 mm/yr. This agrees with known data on the development of glaciers.

The deviation of an annual mean of the sea level from normal sea level, i.e. from the regression line in the land uplift computation, depends to a large extent on the sea level during winter. The deviation of winter mean sea level, ΔH, is governed by dominating westerly/easterly winds over the North Sea and the Baltic entrance which, in their turn, are governed by the south-north winter mean air pressure difference across the North Sea, Δp_N. The following relation is shown to hold (correlation 0.9), with ΔH in cm and Δp_N in hPa (mbar):

$$\Delta H = 4.17\,\Delta p_N - 12.5 \quad \text{or} \quad \Delta p_N = 0.240\,\Delta H + 3.0$$

The latter version of the above relation can be used to reconstruct the south-north air pressure distribution and, thereby, the dominating winds over northern Europe for all winters back to 1774. Thus the winter mean sea level at Stockholm may serve as a winter climate index for northern Europe, high sea level corresponding to dominating westerly winds with warm winters, low sea level corresponding to dominating easterly winds with cold winters.

The winter mean sea level is shown to have a large variability with some extreme winter sea levels during the first 60 years (1774 – 1840), a significantly smaller variability during the next 100 years (1841 – 1940), and again a significantly larger variability with more extreme winter sea levels during the last 60 years (1941 – 2000). The significance level is, in both cases, 99 %. This reveals long-term changes in the atmospheric winter circulation pattern over northern Europe.

Working Group for Geodynamics

Working Group Report 2002-2006

Hans-Georg Scherneck[1])

Abstract
This report presents the activities of the Working Group for Geodynamics, making use of Internet links in the case of detailed meeting programs and progress monitoring documents. Befor that, however, the stepping-down chairman contemplates the notion of geodynamics and one of the major problems in the formulation and concept of a primary observational parameter, the gravity-uplift ratio.

The Subject Geodynamics
Geodynamics is a wide field in geoscience and is in fact only a vaguely defined discipline. If we collect the all the meaningful views of various representatives in research, we arrive at a wide range of phenomena in the Earth and the terrestrial planets, including some moons, that all have in common that physical force is important, continuum mechanics is needed, and kinematic effects are investigated. Deformation and material redistribution in the terrestrial bodies stand in interaction with forces that are created, either by the deformation processes, by endogenic sources mainly in conjunction with internal heat release, or by exogenic sources, mainly gravitational interaction among the celestial bodies.

The NKG Working Group for geodynamics highlights one special phenomenon, land uplift, or with a more appriориate, more comprehensive term, Glacial Isostatic Adjustment (GIA). However, I would like to refrain from calling the other phenomena step-fatherly treated. Besides measurement of postglacial deformation at the surface and the quest for explanatory models, our group is happy to communicate studies on the phenomena of earth and ocean tides, tidal loading, barometric loading, hydrological loading, free oscillations, what have you, and has been so.

However, given our almost world-unique proprietary of GIA taking place inside our very well infrastructured and accessible countries, and the effects being observable right outside our institutes and eventually inside too, given also the Nordic-wide investment into GNSS tracking and reference networks, and the significant increase in campaigning using absolute gravimeters (AG) during the report period, GIA has received the highest emphasis. This can be concluded looking at our memoranda from the annual meetings. This is also in the tradition from the outset of this working group in 1973.

The preferred observing technique then continued almost to date, namely moving a flock of relative gravimeters (LaCoste-Romberg design) along those east-west lines renowned as the Nordic Gravity lines. Four of them were created drawing mostly from the advice of late Professor Tauno Honkasalo. In order to reduce the effect of mechanically adjusting the set point, the observing points along each were determined to have almost the same gravity value. Thus on our flattened planet, looking at the deviation of each profile from a geographic latitude circle you get an image of roughly the elevation of each point above sea level, northward positive.

A shift has occurred as regards the preferred technique. Around year 2000 it was foreseeable that absolute gravimeters are now more accurate than the portable LaCoste-Romberg spring gravimeters and less complicated to create campaigns for. After the primary investment being done they can also

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be employed more economically, resulting in more points. In all, the waived constraint of having to measure along transects has resulted in a more flexible station network.

Much gratitude is extended to the German Institutes, the IfE at Hannover University, for their GRACE Ground-Truth project, with was an effective injector of spirit and encouragement in our Nordic activities, and BKG for their long and unbroken measurement campaigns, and also showing everybody the potential of AG instruments. And for creating appreciation for long time series, tedious work, that is always prone to be made oblivious if ignorant funding decisions would be made. Any one individual in our groups knows of this risk from his/her own experience.

Working group activities 2002-2006

Most conspicuously, the Working Group meetings held annually have been increasing in terms of attendance, peaking in Masala, Finland, in 2005. Also the number of extraboreal participants have been increasing (from north to south: Estonians, Lithuanians, and Germans). We are very happy and proud to have international cooperation with the University of Hannover's Institut fuer Erdwissen-schaft, with Bundesamt fuer Kartographie und Geodäsie, both in Germany, coordinating projects that have both inspired and heralded our swap to absolute gravity. We are participating in the European Combined Gravity Network, and through NGOS we contribute a distributed observation resource to GGOS. For a more specific list of items in our meetings please download the accompanying Power-Point presentation from the web page http://www.oso.chalmers.se/~hgs/NKGWG/ A new cooperative with the Royal Observatory in Brussels has been envisaged in 2006. To end this paragraph let me just list dates and places, April 29, 2003, Copenhagen; April 15, 2004, Gävle; May 3, 2005, Masala; April 15, 2006, Ås.

The major achievement just prior to 2002 was the formulation of an Absolute Gravity plan, which we conceived as a component of NGOS. The plan devises a network of gravity stations (see Figure 3), most of them collocated with GNSS or with points on the relative gravity lines (or both), many enough to obtain a subcontinent-wide representative set of observations, and few enough so they can be remeasured annually or bi-annually. The plan will probably/hopefully last for a 30 years period, and rather grow in temporal and spatial density. This document was updated in 2003 and is available from our home page (quick route: http://www.oso.chalmers.se/~hgs/NKGWG/Docs/Abs_Grav_Plan.pdf).

The Working Group has generated some spin-off. We have been active to propose a sub-network of stations that participate in the European Combined Gravity Network (ECGN, Tab ??), the selection requirement being collocation of an AG-point with a continuous GNSS station and preferably a tide gauge. We have also early brought up the need for a sharply aimed, operative umbrella spanning over the techniques that we geodesists in the Nordic countries employ. I am speaking about the Nordic Geodetic Observing System, conceived as a contribution to global such efforts. Things changed along the way; at times we had given it the name Nordic Geodetic and Geodynamic Observing System, but NGOS seems to fit better into the GGOS concept. NGOS is not the scope of this presentation, but you realise that the WGG is a strong contributor. So are we happy to record the formal approbation of GGOS [sic] on behalf of IGOS-P, the global partnership organisation.

The scientific essence and raison d´être for the WGG

Gravity change is the accompanying effect of land uplift in GIA, and it is only partly related to the crustal surface moving up through the free-air gradient of the gravity field. Owing to mass redistribution, in the simplest concept the incremental flow of asthenosphere or upper mantle material into the developing uplift dome, the earth's mass attraction is changed. Actually, if you bring asthenosphere material into the region just enough to "fill the empty pocket", you'll start another loading problem on the mantle underneath, moving some of its (slightly denser) material outward. Thus, operating with asthenosphere densities in the simple Bouguer approach

$$\delta \dot{g} = (\gamma - 2\pi g \rho)\delta \dot{u}$$

will be misleading. Let me refine this statement, it will soon be misleading once our Absolute Gravity measurement records cover a long enough stretch of time. They will in about 15 years time.

So let us contemplate a more complete picture of a whole earth at least radially stratified as a good next step towards refinement. Using the visco-elastic earth model of Milne et al. (2004), the viscous normal mode solution contributed by Jerry Mitrovica (pers. comm.., and Mitrovica et al. 1994), we can compute the ratio $\delta \dot{g} / \delta \dot{u}$ for a more complicated earth (spherical, PREM-layered, visco-elastic). It turns out that if we model the deformation quite long time after the loading event, the actual ice load history is only of secondary importance. The amplitude cancels out of the ratio expression, the only requirement being that the deforming mantle layers contribute equally much with the simple ice history as with a realistic.

In the language of load Love numbers, the expression for the ratio for each spherical harmonic degree *n* is

$$\frac{\delta \dot{g}_n}{\delta \dot{u}_n} = \frac{2h_n^{'} - (n-1)k_n^{'}}{h_n^{'}}$$

and it turns out that this is not a constant with respect to the spherical harmonic degree, i.e. (n-1) k'_n is not proportional to $h'n$. Since out rebound area's peaks in the spectrum near n=20 and the Laurentide area at n=12, the respective terms are weighted up and tone the ratio. The Laurentide gravity ratio becomes smaller than the Fennoscandian one.

For more detail, consider each observable being composed of spherical harmonics and filtered by the load Love number, and that we need to start in the Laplace domain (the domain exhausted with the variable *s*), since each normal-mode is excited by a Heaviside step at time *T* before present

$$\tilde{\psi}_{nm}(s) = \frac{1}{s} e^{-sT} \Psi_{nm}$$

where Ψ_{nm} is the spherical harmonic development coefficient of the gravity potential of the ice sheet (or one unloading step of it; the complete ice history can be decomposed linearly into individual time steps of arbitrarily small, disintegrating ice prisms). Then the observables can be decomposed as

$$\tilde{u}(s) = \frac{1}{g} \sum_n \sum_\mu {}_\mu \tilde{h}_n^{'}(s) \sum_m \tilde{\psi}_{nm}(s) Y_{nm}(\vartheta, \lambda)$$

$$\delta\tilde{g}(s) = \frac{1}{a} \sum_n \sum_\mu [2_\mu \tilde{h}_n^{'}(s) - (n-1)_\mu \tilde{k}_n^{'}(s)] \sum_m \tilde{\psi}_{nm}(s) Y_{nm}(\vartheta, \lambda)$$

where *a* is the radius of the earth. Each Love function in the Laplace domain is of the form

$${}_\mu \tilde{h}_n^{'}(s) = {}_\mu H_n^{'} \frac{1}{s - s_\mu} \Leftarrow \text{Laplace}^{-1} \Rightarrow {}_\mu h_n^{'}(t) = {}_\mu H_n^{'} e^{-s_\mu t}$$

which are the impulse reponse functions. (In the Laplace domain, the input impulse is multiplied with the transformed Heaviside function, and forming the output of the supposedly linear system earth, the product is once more multiplied with the earth response, decaying exponentials, the temporally decaying exponentials, which are the one-over *s* minus the individual mode's s_μ.

The last step needed here is to recall the Laplace transform lesson from our math classes, namely

$$\text{if}\quad y(t) \Leftarrow \text{Laplace} \Rightarrow \tilde{y}(s) \quad \text{then} \quad \frac{dy}{dt} \Leftarrow \text{Laplace} \Rightarrow s\tilde{y}(s) - y(t=0)$$

and we are able to formulate uplift and gravity change on the basis of the visco-elastic normal modes of the earth; note the mode summation over index μ, which is a ante-subscript to the load Love numbers as they trickle out of the search engine. When the strength falls below a certain threshold, the μ-summation can be terminated. Each

In summary, when $t << T$ the ratio $\delta \dot{g} / \delta \dot{u}$ is rather constant for a given slab of ice, but is dependent on the horizontal extent of the slab.

Now some examples and consequences in pictures. The simple model provides a relation between observed gravity-uplift-ratio, that is shown in Fig. 1. For a PREM-like asthenosphere, the simple model predicts a gravity change of -0.159 to -0.160 µGal/mm, if the ice sheet was large enough so the Bouguer concept is viable. Since the depth of the asthenosphere is on the order of 200 km and the width of the Fennoscandian ice sheet was on the order of 2000 km, Bouguer is supposed to do a good job. However, the concept falls short of contemplating the consequences of lithosphere elasticity and mantle viscous layering.

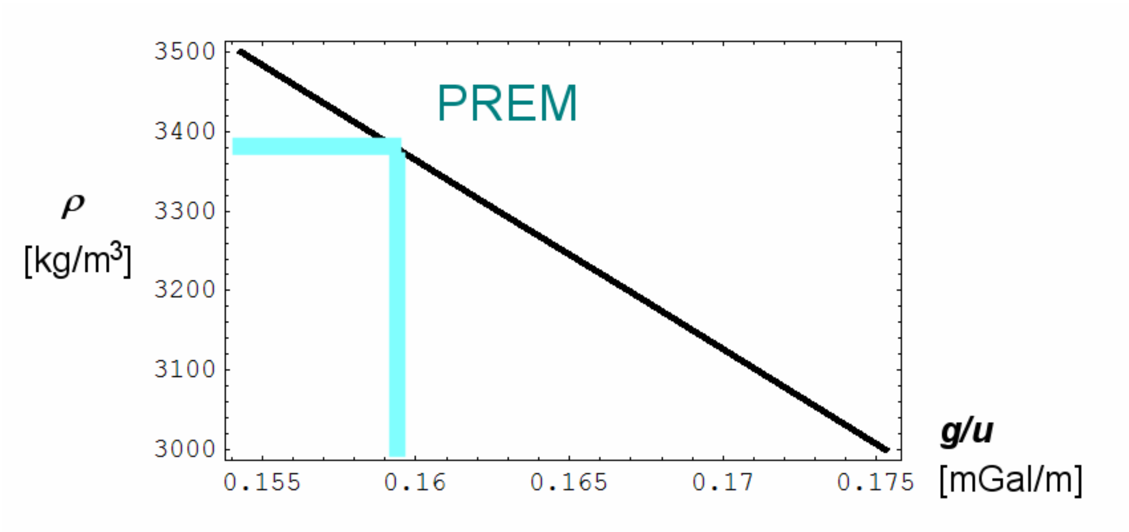

Fig. 1: Using the simple Bouguer relation and assuming the gravity change is contributed by only one, the most competent, layer (the asthenosphere), the density given by PREM corresponds to a gravity change of 0.159 mGal per meter of uplift. However, in a spherical Earth model the uplift gravity ratio depends on the dominant wavelength, and the permissible range for the ratio at each harmonic degree exceeds the abscissa range of this diagram.

For my next thought, I keep the density structure of the PREM model and look at the spherical harmonic relaxation spectrum of two different ice sheets, the Fennoscandian (small) and all Pleistocene ice sheets together (large) at the Last Glacial Maximum (LGM). The excitation spectrum is easily inspected using the degree variances of the loading potential

$$\Psi_n^2 = \sum_{-N \le m \le N} \Psi_{nm}^2$$

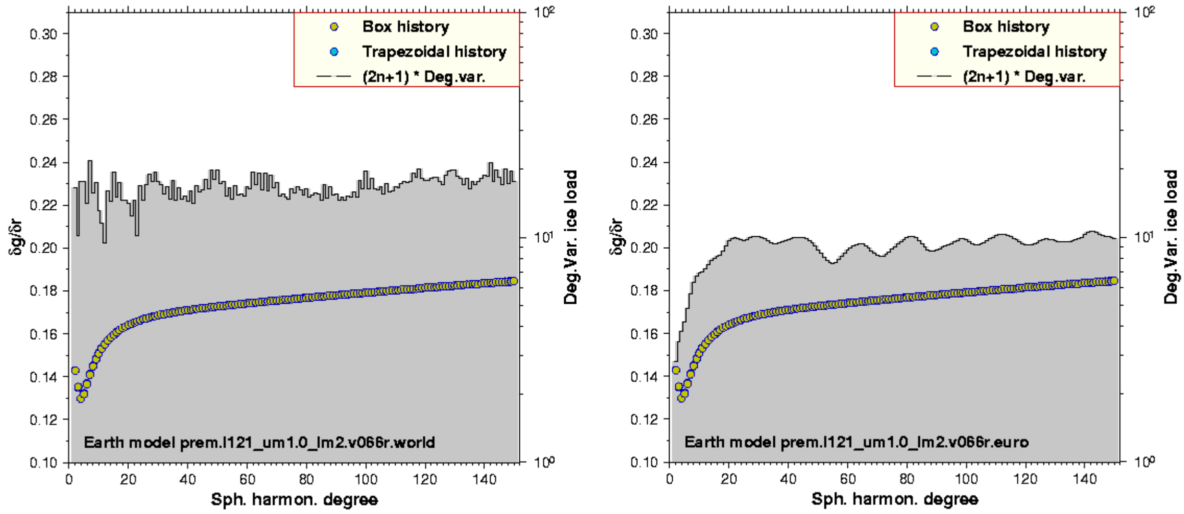

Figure 2: Degree variances of the ice sheet loads at Last Glacial Maximum, left frame all ice sheets, right frame the Fennoscandian (grey walls), and the gravity-uplift-ratio for each harmonic degree (circles). The larger ice sheets excite more of the low degrees, and thus produce a smaller g-u-ratio in toto.

Since the global distribution has an almost constant spectrum (see Figure 2) the low-degree response contributes more to the gravity-uplift-ratio than in the case of the small ice sheet. The gravity-uplift-ratio increases with the spherical harmonic degree, so we can easily see that the ratio will be larger for smaller ice sheets and vice versa. The admissible range of -0.15 to -0.18 μGal/mm can be translated into a misinterpreted asthenosphere density which is in the range of 2900 to 3600 kg/m^3. For a seismologist this is a pathetic result. So crap the simple model.

It might be nice to start off with it when we talk to the informed layman, but in professional matters we have to think of something better. For instance the approach above.

A link to watch AG-progress by

The records of AG progress is compiled in an Excel document, also this one available from the internet (http://www.oso.chalmers.se/~hgs/NKGWG/Docs/Nordic_absgrav_progress_Upto05.pdf). AG-work even exceeded the AG-Plan, and more stations were created, and some of them became better equipped than first foreseen, thanks to the support from our agencies. And not least thanks to the cooperative project with IfE.

The Future

The Working Group of Geodynamics expects from the future, that the NGOS(AG-Plan will be realised, that the number of instruments will grow (Lantmäteriverket has put an order for an FG-5 in early August 2066), and that our investigation will be followed up by exciting and enlightening publications. We can also be sure of a growing number of international projects in which our members participate, and some which are/may be coordinated within our WG.

A personal good-bye

Stepping down from the chair not having been kicked or received kind suggestions to, I would like to pass over the relay pin to Martin Lidberg not with an abrupt stop for my part. Motivation to step down has been composed of wishes to bring more from the BIFROST project into this group instead of writing agendas and getting exhausted from the moderatorship. We also have enough young members in our group so we don't need to go through a phase of Breshnewisation; we're vital. A group so well committed does not require a firm hand for leadership – that's what I have gratefully recorded. Casual glitches of memory and slight of tongue have been kindly remedied or mercifully forgiven, respectively. So thanks for a nice time. I'll continue to come to the annual meetings and enjoy them and the work together with the members. And – Wish you all the best, Martin!

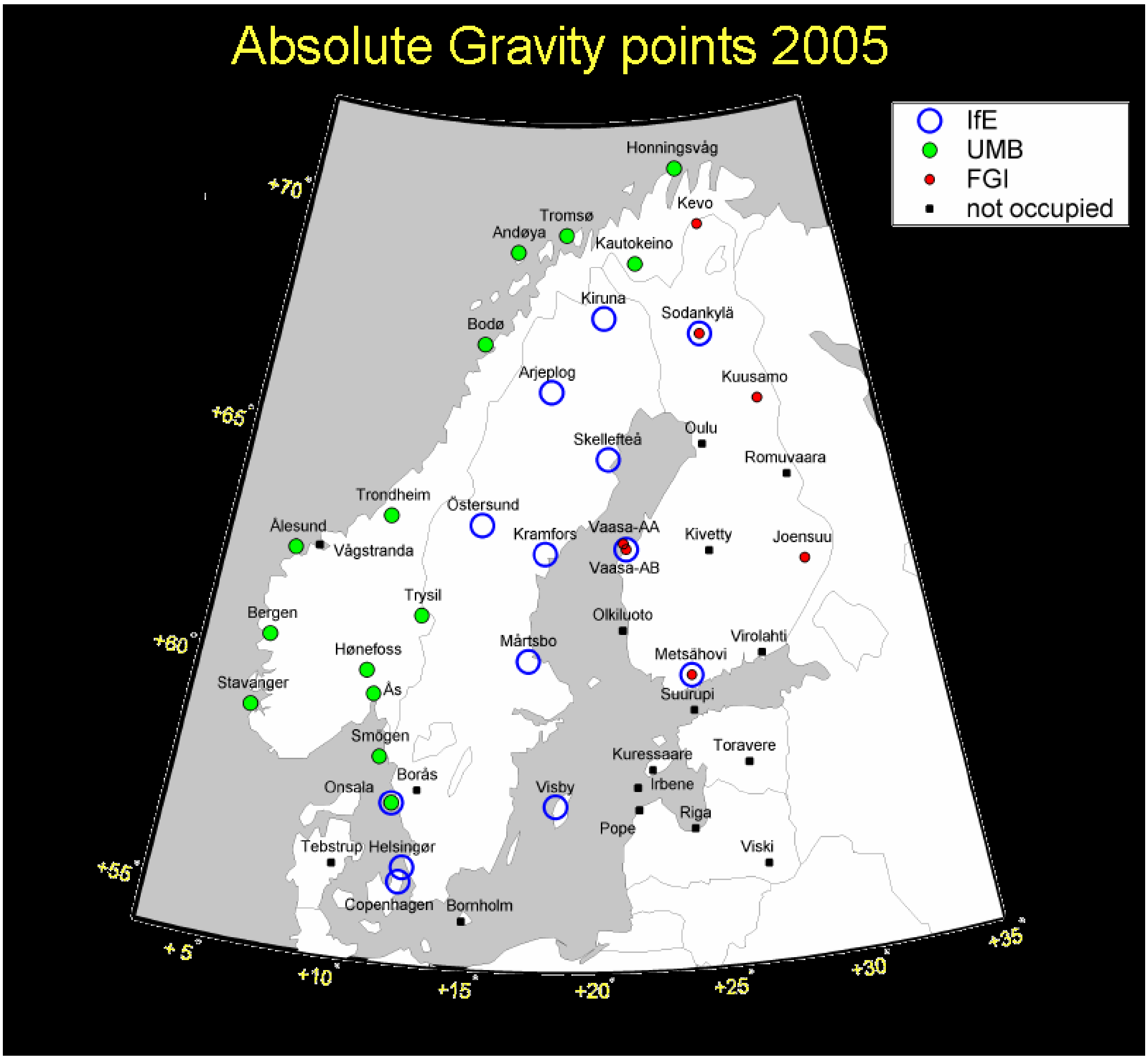

Figure 3. Network of Absolute Gravity points according to the NGOS/AG-Plan

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Absolute Gravimetry in Tectonically Active areas: the Fennoscandian Land Uplift

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Abstract. Absolute gravimetry has reached an operational state on the accuracy level of ±2 to ±3 μGal. This measurement technique is now a geodetic tool to establish large-scale gravity control either to monitor vertical surface displacements only, e.g. at tide gauge stations, or to observe gravimetric changes which is directed to geodynamic research. Major advantages can be made using absolute gravimetry not only as a stand-alone method but complementary to geometrical approaches like GPS and VLBI. With the development of the satellite gravimetry system GRACE, the land-bound techniques are challenged to support the GRACE data evaluation by providing “ground truth” information. Because of its extension and the linearity of the raising, the Fennoscandian land uplift area offers a unique opportunity for validating and testing the GRACE experiment. The continuous mass redistributions in the solid Earth, in the atmosphere and the hydrosphere, cause an integrated effect in the gravity observations. Thus, accurate reduction models have to be established to separate non-tectonic gravity variations (atmospheric and hydrological mass flow) from changes originated from recent tectonics. Besides absolute gravimetry, stationary superconducting gravimetry stations may become an important part for developing and validating precise reduction models. Relative field gravimeters are still important instruments allowing gradient measurements and centring to safety points at the absolute stations.

Keywords: Absolute Gravimetry, Relative Gravimetry, Fennoscandia, Postglacial Rebound (PGR), Geoid Change, GRACE Validation, Geodynamics

Modelling Glacial Isostatic Adjustment in Fennoscandia

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We present an overview of the Glacial Isostatic Adjustment (GIA) process. Numerical modeling of this process allows us to predict a number of observables and therefore make inferences of model parameters, such as 1D earth viscosity structure and Late Pleistocene ice sheet evolution. In this talk we will focus on the distribution of present-day solid surface deformation in Fennoscandia, as determined by the BIFROST GPS network. A state-of-the-art GIA model is used to invert the observed deformation rates and provide insight into the 1D Earth structure and ice history of this region.

A small residual remains when the observed uplift rates are subtracted from the numerical predictions. We postulate that this misfit may be accounted for by considering lateral variations in lithospheric thickness and mantle viscosity in the GIA models, and investigate the effect of 3D Earth structure on the isostatic adjustment of the solid Earth in response to loading during the last glacial cycle.

Our results show that the inclusion of 3D structure in GIA calculations for Fennoscandia introduces perturbations which exceed the present observational uncertainty. Consequently, inferences of earth structure and ice history will be biased if full 3D earth structure is not considered.

Ice history remains the principal factor governing GIA, and preliminary results using a glaciologically realistic Fennoscandian ice model are presented. Such models may be calibrated using observations of relative sea level and present-day rates of deformation.

PGR in Greenland detected using GPS; An overview.

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Here we give an overview of present and future GPS activities in Greenland.

We use data from a network of continuously operating GPS receivers to measure the ongoing crustal deformation due to glacial isostatic adjustment (GIA). The network counts five GPS sites, which have measured over a time period longer than three year. However, during 2006 new GPS sites will be installed and by the end of 2006 the network will count more than 12 permanent operating GPS sites in Greenland. The GPS sites are operated by University of Colorado at Boulder, the European Center for Geodynamics and Seismology and The Danish National Space Center.

The GOCINA Mean Dynamic Topography Models and Impact on Ocean Circulation Modelling

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A major goal of the EU project GOCINA (Geoid and Ocean Circulation In the North Atlantic) was to determine an accurate mean dynamic topography model in the region between Greenland and the UK.

The impact of the new improved mean dynamic topography on the modelling of volume and heat transport in the GOCINA area has been tested using three existing operational systems (FOAM, TOPAZ, and MERCATOR). The volume transports through the straits between Greenland and the UK have been validated against oceanographic observations. In the three operating systems the GOCINA MDT was used for the assimilation of satellite altimetry. In all cases, the use of the GOCINA MDT improved the modelling of the transports and increased the agreement with the observations. The use of the new GOCINA MDT decreased the modelled net northward heat transport through the straits between Greenland and the UK. Furthermore, the GOCINA MDT associated simulations of the Atlantic Thermohaline circulation show improvements.

Finally, the GOCINA project will support the GOCE mission in two distinct cases, namely (1) to educate and prepare the community in using GOCE data for oceanography including sea level and climate research as well as operational prediction; and (2) to develop methods for generating regional gravity fields and to use them to generate a best possible regional gravity field and geoid model for the North Atlantic that can be used in validation of the GOCE products.

Sea ice freeboard and mean sea surface in the Arctic Ocean derived from ICESat

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In this presentation we will estimate sea ice freeboards and mean sea surface in the Arctic Ocean up to 86°N using altimetry data from NASA's laser satellite ICESat. The method adopted here, was originally developed to estimate sea ice freeboards in the Arctic from airborne lidar campaigns. The technique uses the geoid to approximate the mean sea surface and a lowest level filtering algorithm is applied to find the lowest levels, which are believed to represent the open leads in between the ice floes and thus represent the sea surface, and by fitting a smooth curve between the lowest levels using least-square collocation. The Arctic Ocean-wide freeboard maps show good correlation, when compared to QuikSCAT scatterometer data. The information of both the freeboards and the mean sea surface can be implemented in the present gravity models of the Arctic Ocean to improve the gravity field in areas with poor or sparse data.

Detection of changes in building coverage using digital and analogue aerial images.

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Abstract

A building detection algorithm is described and results obtained using imagery captured by analogue as well as digital cameras, are compared for a suburban test site. The algorithm performs well both for verification of existing buildings and detection of new buildings. The results from the four channel digital input data, which includes an near-infrared channel shows to be superior to the analogue three channel data.

1 Introduction

Digital map databases with fully three dimensional (3D) registrations have come into widespread use during the last decade; examples include the Dutch TOP10Vector, the German ATKIS (AdV, 1988), and the Danish TOP10DK (Kort & Matrikelstyrelsen, 2001) products.

Once developed, such databases require continuous investments in revision/update to remain reasonable representations of the actual landscape. Revision of map data typically involves much tedious human activity (stereo analysts visually inspecting, in minute detail, the existing map, comparing with a set of new aerial stereo photos). This implies that map revision is extremely costly, so research in subjects related to full or partial automation of the process could potentially lead to dramatic cost reductions.

Buildings (and roads) are some of the most important topographic objects and in the last few years a number of algorithms for automated registration of buildings have appeared (Fischer et al., 1998, 1999; Süveg, 2003; Süveg and Vosselman, 2004); these algorithms do, however, often depend on the availability of a good first guess for the 2D position of a potential building.

As noted by Baltsavias (2004), generating the first guesses is far from trivial where no previous registrations are available, i.e. in the case of new objects. Nevertheless, the primary aim of this paper is to present a simple algorithm for change detection in the building theme of a digital 3D map database—a task which can be broken down to two related sub-tasks: 1) to verify the existing registrations; and 2) to generate first guesses for the position of new buildings. A secondary aim is to compare the relative merits wrt. building detection, of traditional analogue aerial images and newer four channel digital imagery.

2 Related work

Some notable related work has been carried out in connection with research in update procedures for the Swiss VECTOR25 map product Baltsavias (2004, 2002); Eidenbenz et al. (2000); Niederöst (2000, 2001, 2003) and the German ATKIS map product Walter (2004); Walter and Fritsch (2000).

The work by Niederöst (2000, 2001, 2003) was highly successful in assigning heights to the basic 2D registrations from VECTOR25, and in doing automated building reconstruction and de-generalization from various combinations of stereo views, orthophotos and digital surface models (DSMs). Our algorithm is much more narrow in its scope (validation and change detection; no reconstruction) than the ones developed by Niederöst. On the other hand, it only relies on the height information included in the existing map data—no orthophotos, no DSMs.

The work by Walter (2000, 2004) was based on unsupervised classification of image data segments defined using the existing ATKIS registrations of buildings and roads. Its aim was primarily to detect changes in overall land use patterns, i.e. changes from forest or other vegetation coverage to industrial or residential use. This involves detection of the general distribution of buildings (which was done with a very high degree of success). In our case, the interest is in detecting changes in individual building registrations. We do however, follow Walter's procedure of using existing map registrations in a segmentation used for generation of training sets. In the detection step on the other hand, we use an image segmentation based on pixel colour.

3 Algorithm

The algorithm presented below relies on a purely spectral recognition of roofs. This is based on the assumption that the number of commonly used roofing materials is relatively sparse (tile, roofing felt, slate, and only a few others). Additionally it is assumed that the number of changes (new build-

ings and demolitions) is small compared to the total number of buildings.
The method is initialized with a 3 step process:

1. segmentation of the input image using the EDISON algorithm Christoudias et al. (2002)

2. projection of the existing 3D building registrations onto the segmented image

3. extraction of a group of segments already registered as buildings (these segments define the set of potential roofing material spectra)

Then the following 3 steps are carried out for *each* segment in the segmented image

4. locate N spectrally nearest neighbours

5. count n, the number of the N segments which are already registered as buildings

6. building detection: if n is large enough, register the current segment as a potential building

Finally the change map is generated through these 3 steps

7. extend detection registrations so an existing building registration is considered verified if more than m% of the object is detected.

8. subtract the existing registrations from the new set of building detections to get a preliminary change map

9. clean up the preliminary change map using (a.o.) morphological operations to eliminate small and thin elongated clusters (small changes should be ignored and thin elongated clusters typically arise from minor misregistrations

In the case of four channel digital imagery we add some additional steps: first we split the four channels (near-infrared (N), red (R), green (G), blue (B)) into two spectrally overlapping three channel images: NRG and RGB; each of these are run through the nine step algorithm above. Then the two results are combined using these criteria:

10. an existing building registration is considered verified if it is verified in at least one of the images (i.e.: a priori, we have reason to believe that a building is there, so a weak indication is OK).

11. new buildings are only accepted if detected in both NRG *and* RGB (i.e. a priori, we have no reason to believe that a building is there, so we want more hard evidence)

4 Data

In this study we compare an analogue and a digital data set. The analogue data set was digitized from a true colour photograph captured by a traditional photogrammetric large format (230 mm × 230 mm) camera. The digital data set was captured by the relatively new Vexcel *UltraCam*$_D^{TM}$ Leberl et al. (2003).

Both data sets were captured and post processed with the purpose of updating digital map data in a traditional photogrammetric production flow. This means, a.o. that the images have been colour adjusted for large scale colour uniformity (i.e. *dodging*). In other words, even the digital data used are not necessarily spectrally reliable: we cannot expect to be able to recognize sample spectra of roofing materials in the images; rather, the 3D registrations from the map database are used to extract the training data for the detection algorithm.

4.1 Test site

The test site used in this study is a small subset of a full photogrammetric scene: approximately 400 m × 250 m (i.e. 10 hectares) north-east of Odense, in central Denmark. The test site is typical suburban, primarily characterized by detached single family houses surrounded by small vegetated gardens (cf. figures 1–2).

5 Results

5.1 Analogue data

The results obtained from the algorithm, using analogue input data and parameters $N = 25$, $n = 5$ and $m = 30$, are shown in figure 1.

The dataset contains 99 buildings of which 6 are located on the edge of the image, with only a small fraction of the building entering the area. These cases are referred to as *border cases* below. Since no new buildings have been built, we have randomly selected 10 buildings for removal from the dataset (accidentially, one of these showed to be a border case). These buildings (referred to as *the validation set* below) are marked up with a blue mask slightly larger than the original registration, in the figure.

The nine (non-border case) buildings from the validation set are all detected to some extent (detection is shown in red inside the blue frame). Four of them are detected completely or almost completely. The remaining 5 are only detected for a minor part of the building, but since we are primarily interested in flagging potential buildings, we only need to detect a minor part to fulfill our goal.

The *verification* part of the algorithm is illustrated by the green and yellow markers on the figure: green indicates redetected (i.e. verified) objects, while yellow indicates existing registrations which cannot be verified. In the analogue case we verify 75 buildings and cannot verify 14 (of which 5 are

Figure 1: *Upper left:* Analogue aerial image. *Upper right:* After segmentation. *Lower:* Final result—see main text for interpretation of colour coding.

Figure 2: *Upper left:* Digital aerial image. *Upper right:* After segmentation. *Center left:* Partial result, RGB. *Center right:* Partial result, NRG. *Lower:* Final result—see main text for interpretation of colour coding.

border cases). One of the non-verified buildings is quite unusual by having a blue roof. No other building in the area has similar roofing material, making this type of roofing material uncovered or badly represented in the training set.

The 48 red markers on figure 1 *outside* the blue validation set indicates potential new buildings. A large part of these actually correspond to buildings or building-like objects (carports, outhouses, sheds, garages) which are not to be registered in the map database according to the registration instruction.

5.2 Digital data

The results obtained from the extended four channel algorithm, using digital input data and parameters $N = 25$, $n = 5$ and $m = 30$, are shown in figure 2. The dataset contains 99 buildings of which 3 are border cases.

The 10 buildings from the validation set are all detected, eight of them completely (note: in figure 2, detection of validation objects is masked with green inside the blue frame—nondetected parts are shown in yellow).

All buildings, except for two (and a tiny border case), are verified by the algorithm. One of the non-verified buildings is the same blue-roof building described above.

As for the analogue case, there is a comparatively large number (38) of indications of potential new buildings. Comments made in the analog case also applies here.

6 Discussion and Conclusion

In both the analogue and the digital case, the results are quite satisfactory with respect to validation and verification. The indications of potential new buildings still contains too many false alarms caused by non-buildings as well as building-like structures. The false alarms caused by non-buildings are probably the easiest to get rid of, e.g. by adding additional texture measures to the classification/detection process. Getting rid of the remaining false alarms, caused by building-like structures is far more difficult since they are actually buildings and require human interpretation to decide whether they fit in with the registration instruction or not. A potential solution could be to extend the existing map data base with information about known objects which should not be included.

Comparing the two results from the analogue and the digital datasets it can be seen that the most complete result with respect to both validation and verification is (not surprising) the one based on digital data.

The digital dataset is originally captured at a quantization of 12 bits/channel, whereas the analogue dataset is scanned at a quantization of 8 bits/channel. Subsequently, the digital dataset is spectrally remapped to 8 bits/channel, resulting in information loss. Especially in shady regions, such as the north facing part of gable roofs, we could expect to be able to gather much more useful information using the full data set. As we, however attempt to be able to plug in to a traditional photogrammetric production flow, we currently limit ourselves to using the adapted dataset. When digital photogrammetric workstations in general become more capable of using high radiometric quantification levels (12–16 bits/channel), this limitation will disappear.

In conclusion, we find the results of the (actually very simple) algorithm quite satisfactory, especially in the case of digital data. There is still room for improvements, primarily with respect to the reduction of false alarms. Also, it should be noted that the algorithm depends on a strong contrast between the target object types and the background. In a case of industrial flat-roof roofing felt situated on asphalt covered parking lots, the algorithm will most probably fail.

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The Struve Geodetic Arc on the UNESCO List of Heritage.

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In 2005 The Struve Geodetic Arc was inscribed in UNESCO List of Heritage after ten years of preparations to get it accepted on the list. The Struve Geodetic Arc was earlier known as The Russian Scandinavian Meridian Arc. It is the longest Meridian Arc ever observed and it was measured between 1816 and 1855. The Arc was some 25 degrees of latitude in length, and ran approximately along the 25th meridian of east longitude, from the Danube (Donau) River Valley in Ukraine northward through Russia, Finland and Sweden to the North Norwegian Coast. Given the absence of modern conveniences, this was clearly an enormous undertaking, involving a great deal of complicated fieldwork and computations, where geodesists from both Russia, Finland and Scandinavia participated. The Struve Geodetic Arc gave a significant contribution to the science of geodesy.

From Normal Height to Orthometric Height and From Quasigeoid to Geoid

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Abstract

Many vertical geodetic systems are defined in terms of *normal heights*, and the *quasigeoid* plays a role, e.g., in GPS-levelling. The main advantages of these height concepts are that both can be determined without any information on the topographic mass density distribution.

Nevertheless, the *orthometric height* and the *geoid* are still of much interest, and usually the correction from normal height to orthometric height (dH), which is also the minus of the quasigeoid to geoid height correction, is estimated by a term related with the simple Bouguer anomaly times the normal height. Not even in the highest mountains of Scandinavia this term should exceed 0.5 m

In this article we refine the formula for dH by adding two terms related with the roughness of the topography (terrain correction) as well as the lateral variation of the topographic density. It is shown that the first of these new terms may be as significant as the Bouguer anomaly related term, and the magnitude of the second term could reach some decimetre.

1 Theory

The *geodetic height* (h), frequently denoted ellipsoidal height, can be decomposed into the orthometric height (reduced for curvature; the correction is practically negligible) H' and geoid height N, or normal height H^N and height anomaly ζ :

$$h = H' + N = H^N + \zeta . \tag{1}$$

Eq. (1) yields the formal conversion from normal height to orthometric height, which is the minus of the conversion from quasigeoid to geoid height:

$$dH = H' - H^N = \zeta - N . \tag{2}$$

From Bruns' formula (Heiskanen and Moritz 1967, Sect. 2-13) applied twice to the last part of Eq. (2) we obtain:

$$dH_P = \frac{T_P - T_g}{\gamma_0} + d\zeta_P , \tag{3a}$$

where γ_0 is normal gravity at the reference ellipsoid, T_P and T_g are the disturbing potentials at the computation point P and geoid, respectively, and (with Q located at normal height):

$$d\zeta_P = \zeta_P \left(1 - \gamma_Q / \gamma_0\right). \tag{3b}$$

Eq. (3a) can be rewritten

$$dH_P = -\frac{dT_P^{nt} + DV^t}{\gamma_0} - dN_{\Delta\mu} + d\zeta_P , \tag{4}$$

where dT^{nt} is the no-topography disturbing potential difference, DV^t is the topographic potential difference (both previous terms refer to standard density μ_0), and $dN_{\Delta\mu}$ is the geoid correction for lateral topographic density changes.

Using Stokes' original and extended formulae for dT^{nt} and considering the boundary condition of physical geodesy (Heiskanen and Moritz 1967, p. 86), we obtain after a few manipulations the equation

$$dT_P^{nt} = \Delta g^{nt} H_P + \left(\gamma_Q - \gamma_P\right) H_P + I_P , \tag{5a}$$

where

$$I_P = \frac{R}{4\pi}\iint_\sigma \left[S(\psi) - S(r_P,\psi) + H_P \frac{\partial S(r_P,\psi)}{\partial h_P} \right] \left(\Delta g^{nt}\right)^* d\sigma \quad . \tag{5b}$$

Here $S(\psi)$ and $S(r_P,\psi)$ are Stokes' original and extended functions, and $(\ )^*$ denotes that the no-topography gravity anomaly (Δg^{nt}) is downward continued to sea level.

Inserting Eq. (5a) into Eq. (4), we arrive at the following formula for the conversion of normal height to orthometric height (for details, see Sjöberg 2006):

$$dH_P = -\frac{\Delta g_B}{\gamma_0} H_P + dH_P^R - \frac{I_P}{\gamma_0} - dN_{\Delta\mu} + D\zeta_P \ , \tag{6}$$

where the first term is the traditional term based on the Bouguer anomaly,

$$I_P/\gamma_0 \approx \Delta \bar{g} \frac{H_P^2 s_0^2}{\left(s_0^2 + H_P^2\right)^{3/2}} \ , \tag{7}$$

where $\Delta\bar{g}$ is the mean gravity in the area, s_0 is the extension of the local integration area (say, to 100 km), dH^R is a topography roughness term (being zero for flat terrain), and

$$D\zeta_P = d\zeta_P + \zeta_P H_P \left(\gamma_P - \gamma_Q\right)/\gamma_0 \approx -2\zeta_P^2/R \approx 0 \, . \tag{8}$$

2 Numerical results

Some numerical examples of the significant terms of Eq. (6) with topographic elevations limited to those in Scandinavia are presented in Table 1. It shows that the topography roughness term dH_P^R may be as significant as the Bouguer anomaly term.

Table 1. Numerical estimates in metres of terms of Eq. (6) for standard topographic density $\mu_0 = Gx2.67[g/cm^{-3}]$ with G = gravitational constant, $\Delta g_B = 200$ [mGal], $\gamma_0 = 0.981$ [kGal], $s_0 = 100$ [km] and various H_P

Term/H_P[km]	0.5	1	2	2.5	
$\Delta g_B H_P/\gamma_0$	0.13	0.26	0.51	0.64	1) $dN_{\Delta\mu} \approx -\frac{2\pi\Delta\mu}{\gamma_0} H_P^2$
$\lvert dN_{\Delta\mu}\rvert$ 1) $\rightarrow \frac{\Delta\mu}{\mu_0}$	x0.03	x0.11	x0.45	x0.71	2) $\frac{I_P}{\gamma_0} \approx \frac{\Delta\bar{g}}{2\gamma_0 s_0} H_P^2$ for some mean $\Delta\bar{g}$.
I_P/γ_0 2)	0	0	0	0.01	3) $dH_P^R = \frac{H_P dg^t - dV^t}{\gamma_0} \approx \frac{\pi\mu_0}{2\gamma_0}\bar{H}\left[3H_P + \bar{H}\right]$
dH_P^R 3)	0.01	0.06	0.23	0.36	for some mean $\bar{H}$.

3 Conclusions

The conclusions can be summarized as follows:

- The refined formula for the conversion from normal height to orthometric height becomes:

$$dH_P \approx -\frac{\Delta g_B}{\gamma_0} H_P + dH_P^R - dN_{\Delta\mu} \qquad (9)$$

- For rough terrain the topography roughness term dH_P^R could be of the same order as $\Delta g_B / \gamma_0$ or more.
- The effect of lateral topographic density variation $dN_{\Delta\mu}$ could reach a decimetre or more in Scandinavia.
- $-dH_P$ is the conversion from quasigeoid height to geoid height.
- The dwc correction term $-I_P / \gamma_0$ only becomes significant in the highest mountains on Earth.

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Ten years GPS observations to detect local crustal movements

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Abstract

The Finnish Geodetic Institute established, in co-operation with the POSIVA Company, three high precision GPS monitoring networks in 1994-95 at the investigation areas, which were selected as candidates for the final disposal site of the spend nuclear fuel in Finland. The monitoring networks include one permanent GPS station and 6-9 concrete pillars for episodic GPS observations. Each station has a 2-meter high concrete pillar for the antenna mount. The permanent stations belong the Finnish permanent GPS network, *FinnRef*®, which consists of 13 stations.

The size of the local GPS networks is approximately 2x2 km. The average distance between two neighbouring stations is about 1 kilometre. The location of the pillars has been observed once or twice per year using 6-7 Ashtech Z-12 GPS-receivers equipped with Dorne Margolin-type antennas.

The local GPS networks have now been measured altogether 14-21 times. The rates of the baseline lengths obtained by the least square adjustment are so small that only some of them exceed the accuracy of the determination. The theoretical evaluation of the change rate errors yield the result ±0.1 mm/a, which lead to the conclusion that at two investigation areas there are no baselines with change rates of statistically significant at the confidence level of 95%. At the Olkiluoto investigation area we noticed that one third of the baselines have statistically significant change rates.

In order to maintain the uniform scale for the GPS measurements made in different years a baseline for electronic distance measurements (EDM) was established at the Olkiluoto investigation area in 2002. The baseline has been measured already 9 times using precise EDM instruments simultaneously with the GPS observations. The mean difference between GPS and EDM obtained from 8 simultaneous measurements is (0.6 ± 0.2) mm.

Keywords. GPS network, deformation measurement, geodynamics.

1 Introduction

The Finnish Power Company TVO (Teollisuuden Voima Oy) started in 1983 a special research program, including studies in geology, hydrology, geophysics, in order to find a suitable place for disposal of spent nuclear fuel. According to geological studies three places were selected for detailed investigation in 1993. In co-operation with TVO (later Posiva Oy) and the Finnish Geodetic Institute (FGI) took the responsibility to establish GPS monitoring networks on the research areas. The first of the research areas is located on the west coast (Olkiluoto), the second in Central Finland (Kivetty), and the third in northeast Finland (Romuvaara) (Fig. 1). More comprehensive description concerning the motivation of the work and the description of the investigation areas, as well as the establishment of the GPS networks is given in (Chen and Kakkuri 1994).

Each investigation area includes the continuously working permanent GPS station and the high precision local GPS network. At the first investigation area, Olkiluoto, GPS observations have been made twice per year since 1995. At the Kivetty and Romuvaara investigation areas the GPS observations have been made twice per year from 1996 to 2001 and once per year since 2002. The GPS networks have now been measured altogether 21 times at Olkiluoto and 14 times at Kivetty and Romuvaara.

The work and the observation results have been reported by yearly basis. The working reports contain already nine volumes (Chen and Kakkuri 1995, 1996, 1997, 1998; Ollikainen and Kakkuri 1999, 2000; Ollikainen et al. 2001, 2002, 2004; Ahola et al. 2005, 2006). These reports contain altogether more than 1500 pages. It should be mentioned that main part of the numerous pages contains printouts of the GPS computations.

The purpose for the repeated GPS measurement is to investigate the possible crustal movements at the investigation areas. Since we are trying to detect changes in the baseline lengths between the stations, the observation and computation methods should be similar in the course of the years. During ten years elapsed since the first observations at Olkiluoto were made, the GPS system has remained mainly unchanged. Fortunately, we started the measurements at the investigation areas at the time when the development of the GPS antennas and receivers was reached such a level that we have had no need to change the receiver or antenna type to a new and more accurate one. What is the most important: the Dorne-Margolin type antennas used in the observations are still the same, which were used at the beginning.

However, some changes have been made in the observation procedure during the course of the years. At the beginning of the observation period, i.e. in the mid-90s, the accuracy of the GPS determinations was believed to be at sub-millimetre level. As there were no precise time series long enough to show the long-term stability of the GPS determinations, the short time repeatability was regarded as a measure of GPS accuracy.

The satellite constellation is rotating around the earth once in 24 hours. Most part of short period systematic errors are eliminated, if the length of the observation session is 24 hours or its multiple. In the first observation years the observation sessions were 4-6 hours long, but later on the importance of the 24-hour sessions became more evident. The nominal length of the last observation session at Olkiluoto was 48 hours and at Kivetty and at Romuvaara 24 hours.

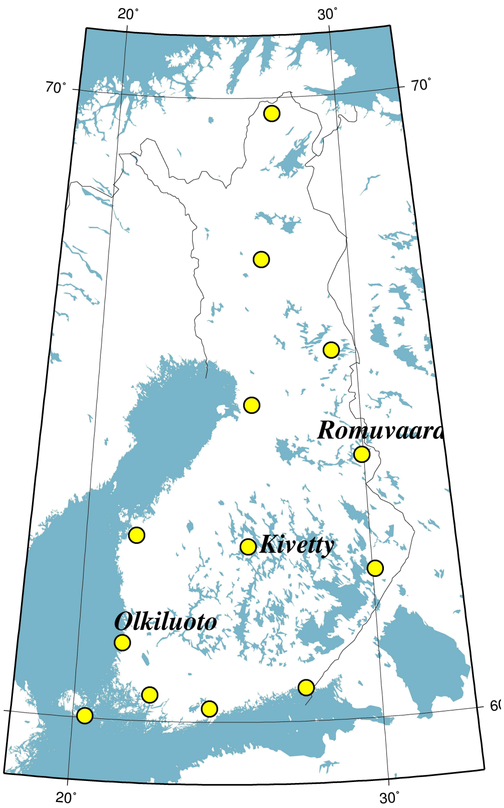

Fig. 1 *The Finnish permanent GPS network, FinnRef®, and the local investigation areas.*

2 The permanent GPS stations

The FGI established in 1994-96 a permanent GPS network called *FinnRef®* (Fig. 1). Four stations (Metsähovi, Vaasa, Joensuu, and Sodankylä) belong to the European-wide permanent EUREF network, besides Metsähovi station belongs to the IGS network. The main objectives for *FinnRef®* are to connect the local reference frames to international ones and to study the land uplift and other regional crustal movements.

The stations were chosen for the intended use of geodynamic research. All stations except one are on bedrock. The stations have open sky at least above 15°, in most cases above 5°. At Olkiluoto, Romuvaara and Kivetty the antenna is mounted on a 2 m tall concrete pillar, two stations have invar-stabilized towers and all the other stations have 2.5 m steel grid masts. The stations are equipped with geodetic dual frequency receivers (Ashtech Z-12) and Dorne Margolin type choke ring antennas. All satellites are tracked above 5° and stored to the memory of the receivers. The recording interval is 30 s. The data is downloaded in every night from all stations, converted to the RINEX format, and archived. (Ollikainen et al. 1997)

Because the the local GPS networks in Olkiluoto, Kivetty and Romuvaara include a *FinnRef®* permanent station the local networks may be connected to the global GPS network such as the IGS network, and thus investigate the regional deformations at the investigation areas by integrating the IGS station at Metsähovi and the corresponding permanent station.

3 The local GPS networks

The local GPS network at Olkiluoto includes 10 stations, and at Kivetty and Romuvaara 7 stations (Figs. 2, 3 and 4). The 2-meter high concrete pillars were built up according to the same principles as the pillar of the permanent GPS station on the area. All pillars were anchored to the solid bedrock with screw bars. The pillars are located in different geological blocks according to the geological studies. The distances between the pillars are from 0.5 km to 3.5 km.

The GPS antennas are mounted on the pillars using the stainless enforcement plates, which confirm that the antenna will be mounted on the same place than earlier by an accuracy of 0.1 mm. There are two reserve benchmarks around all pillars for control surveys. Trees were cut in the surroundings so that there are no obstacles above the elevation angle of 15 degrees. More detailed descriptions concerning the local networks were given in (Chen and Kakkuri 1994, Ollikainen et al. 2004).

3.1 The GPS observations in the local networks

The local GPS networks were observed twice per year during 1995-2001. Hence 2002 the observations were continued twice per year at Olkiluoto, but only once per year at Kivetty and Romuvaara investigation areas. Since 1995 the local network of Olkiluoto has been measured altogether 21 times, while the local networks of Kivetty and Romuvaara have been measured 14 times since 1996.

The observations were made using 6-7 Ashtech Z-12 receivers equipped with Dorne Margolin-type choke ring antennas. The minimum session length was in the first determinations 6 hours, but later on the sessions were prolonged to 24 hours.

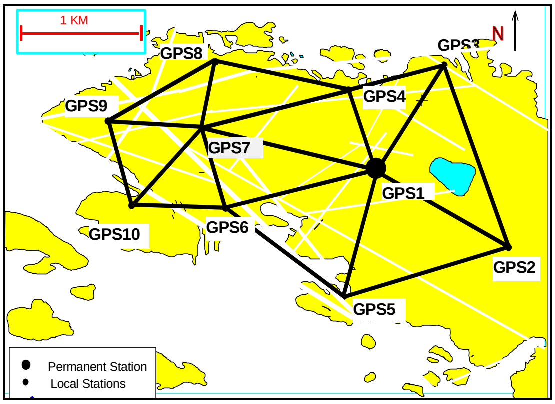

Fig. 2 *The local network at the investigation area of Olkiluoto.*

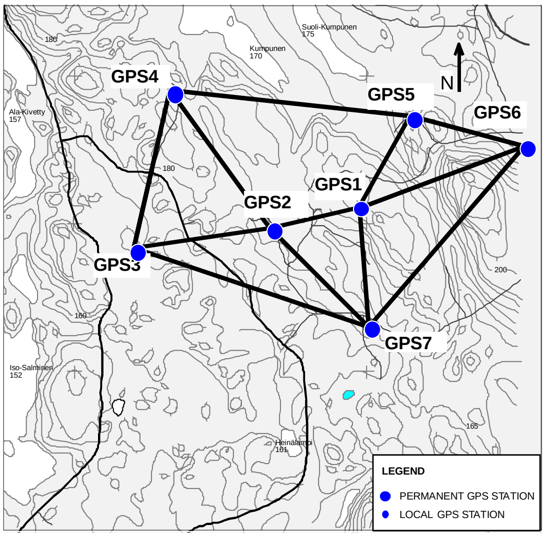

Fig. 3 *The local network at the investigation area of Kivetty.*

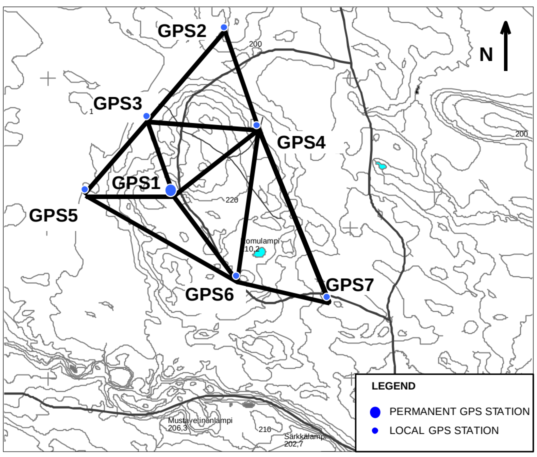

Fig. 4 *The local network at the investigation area of Romuvaara.*

3.2 Processing the GPS observations

The GPS observations have been processed several times, first with the Bernese Ver. 4.0 software (Rothacher and Mervart 1996) then with the Bernese Ver. 4.2 software (Hugentobler et al. 2001), and the last time with Bernese Ver. 5.0 software (Hugentobler et al. 2004). The following options were used in the processing:

- Observations were processed using independent L1 and L2 observations, in order to obtain lower measurement noises and smaller effects of the multipath errors.
- The ionospheric refraction was modelled using the geometry free combination (L4) of the phase observations.
- The L1 and L2 observations were corrected with the estimated ionospheric models in order to remove the absolute scale errors resulted from the ionospheric refraction.
- A global standard atmospheric model, which approximately represents the atmospheric conditions at the observation time, was used to correct the tropospheric refraction in order to remove the scale errors. Local tropospheric parameters were solved in the final solution in order to obtain an unbiased estimation of the height component.
- The ITRF96 coordinates of the permanent stations at each investigation area (Ollikainen et al. 2000) were used as initial coordinates in GPS solution.

4 Analysis of the GPS results at the local networks

4.1 Accuracy of the determination of the baseline length by GPS

The formal accuracy of the GPS solutions carried out by Bernese software was always extremely good. The RMS errors of the coordinates were always smaller than 1 mm; the typical values of the RMS errors were between ±0.1 mm and ±0.2 mm for latitude and longitude and between ±0.5 mm and ±1.0 mm for height. According to our experience (see e.g. Ollikainen 1997, p. 91) we may multiply the RMS errors by a factor of about 10 in order to get a reliable estimation for the precision of the GPS coordinates. Besides, there are several modelling errors, which are varying from year to year, and cannot be estimated.

The only way to estimate the accuracy of episodic GPS determinations is to look at the repeatability of the determinations. The variation of the determinations is the most reliable measure for the precision, but when we study the GPS observations, which were collected during several years, the real movement of the observation stations is included in the variation, too. We studied at first the baseline lengths, because these are free from the changes in the reference frame.

We used the baseline lengths as observables, by computing the RMS of the baseline length deviations from the mean for all baselines at each investigation area. The baseline lengths were handeled by three different ways:

1. The baseline lengths were computed using the coordinates resulted in the GPS observations.
2. The baseline lengths were corrected by the scale correction described in Chap. 4.2.
3. The trend in the baseline length was removed. The trend in the baseline lengths were solved by LSQ method described in Chap. 4.3. The baseline lengths which were corrected by the scale corrections were used as observables.

The RMS of the deviations of all baselines computed by three different methods are shown in Table 1. The repeated determinations of the baseline lengths give an estimation for precision of the observation, which is little bit better than ±1 mm. We will use in the further analyses the RMS of all deviations from the mean, ±0.9 mm, as the baseline measurement accuracy.

Table 1. *The RMS of the baseline length deviations from the mean computed by three different methods at each investigation areas.*

Area	Base-lines	Mean length	RMS of the baseline length deviations from the mean [mm]		
	n	[m]	1	2	3
Olki	45	1711	±0.88	±0.85	±0.75
Kive	21	1433	0.74	0.64	0.57
Romu	21	1087	1.06	0.75	0.63
RMS		1410	±0.90	±0.75	±0.65

4.2 The ionosphere and the scale of the GPS networks

The modelling of the ionosphere yields reliable results when the ionosphere is calm. The observation years (1995-2003) contained, however, some most active ionosphere periods. It was shown in Ollikainen and Kakkuri 1999, that under disturbed ionosphere using the higher order terms in the ionosphere model cause an azimuth dependent bias to the baseline lengths. That is why we decided to use only the lower order terms in ionosphere models, which is also the recommendation of the compilers of the software (Rothacher and Mervart 1996). The question arises how well the lower order ionosphere models describe the rapid changes in the ionosphere. Using the ionosphere model will remove the main part of the ionosphere refraction, but how large is the part, which is not removed by using the model. The unmodelled part result into the baseline lengths an error, which behave like a scale bias.

The accuracy of the GPS determinations depends on how well such factors, which affect to the scale of the system, have been eliminated. We know that all observation sessions are affected more or less by such phenomena, which cause scale biases. This kind of errors should be removed from the results before using them in further investigations, so that the scale biases in different years could not be confused with the change rates of the baselines.

The scale bias is, however, difficult to evaluate, because there is no such a baseline, which could be considered invariant. Fortunately, we have a long series of measurements at each investigation areas, and thus a reliable basis for the baseline lengths. We may derive the scale differences between campaigns using the average baseline lengths as a basis.

The deviations of the individual baseline length from the mean of all determination are here computed in proportional to the length of the baseline:

$$v_i = \frac{(s_i - s)}{s}, \quad \text{where} \tag{1}$$

s = the mean length of the baseline;
s_i = the i^{th} determination of the baseline lengths;
v_i = deviation of the i^{th} determination from the mean in *ppm*.

The scale factor is computed for each observation session according to the formula:

$$\mu = \frac{\sum_{i=1}^{n} v_i}{n}, \quad \text{where} \tag{2}$$

n = number of all baselines determined in the session;
μ = scale factor in *ppm*.

After we have computed the scale factors for each observations sessions, they can be used to correct the individual baseline lengths according to the following formula:

$$s_i^o = (1+\mu)\cdot s_i, \quad \text{where} \tag{3}$$

s_i = observed baseline length;
s_i^o = corrected baseline length.

The scale factors resulting in the computations are shown in Fig. 5, in which we may conclude that in most cases the scale of a session is within the limits of ±0.5 ppm, but some sessions the scale may reach as high values as 1-2 ppm. The highest value (1.5 ppm) was reached at Romuvaara synchronously with the high *TEC* values in Oct. 2002, which indicated difficulties with the ionosphere modelling.

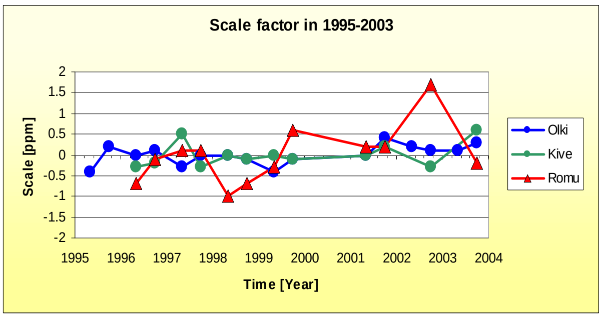

Fig. 5 *The scale factor computed according to Eqs. 1-3 for different session at Olkiluoto (Olki), Kivetty (Kive) and Romuvaara (Romu) in 1995-2003.*

4.3 Change rates of the baseline lengths

The vector lengths between observation stations were solved separately in each observation campaign. The observed vector lengths were reduced to a common scale using the scale factors solved according to Eqs. 1-3. The change rate of the baseline length is the first indicator to show if the network has deformed during the observation span. The change rates of all baselines were solved using linear regression, in which the observations, i.e. the baseline lengths obtained from the GPS solutions, were taken to the adjustment as equally weighted independent observations.

The change rates obtained for different baselines are very small. At Olkiluoto there are only two baselines, in which the change rates exceed 0.2 mm/a. At Kivetty all change rates are less than 0.2 mm/a, but at Romuvaara there are two baselines, in which the change rates exceed 0.3 mm/a. When the accuracy of the change rate obtained from LSQ solution was taken as basis of the evaluation the number of baselines with statistically significant change rates at the confidence level of 95% was 8 at Olkiluoto, at Romuvaara investigation area there were two such baselines, but at Kivetty no such baselines exsist.

5 Horizontal velocities of the GPS stations

5.1 Helmert transformation

In order to get an idea how the different GPS stations move against each other, we have to confirm that all coordinates obtained from GPS computations since 1995 are located to a common coordinate system. The consistency of the coordinates obtained in different years was assured by the following procedure. At first we formed a fictive mean session by computing the average of all coordinates of the sites, after which all coordinate sets were transformed to mean session using 7-parameter *Helmert* transformation. The transformation was made according to following equation:

$$\begin{vmatrix} X \\ Y \\ Z \end{vmatrix}_{\text{Mean}} = (1+m)\cdot\begin{vmatrix} 1 & \varepsilon_z & -\varepsilon_y \\ -\varepsilon_z & 1 & \varepsilon_x \\ \varepsilon_y & -\varepsilon_x & 1 \end{vmatrix}\cdot\begin{vmatrix} X \\ Y \\ Z \end{vmatrix}_{\text{Obs.}} + \begin{vmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{vmatrix} \tag{4}$$

in which the transformation parameters; the coordinate differences of the origins (ΔX, ΔY, ΔZ), the rotation angles around the coordinate axes (ε_x, ε_y, ε_z), and the scale factor (m) were solved by the least squares method from the coordinates obtained in different sessions. The scaling is performed using the scale factor in the transformations. The scale factors solved here should be comparable to those solved by the method, which was described in Chap. 4.2

The coordinates were then centred to the initial coordinates of the permanent GPS-station (GPS1) by a simple coordinate shift, i.e. by adding the coordinate difference at GPS1 to the coordinates of all other GPS stations.

5.2 Horizontal coordinates

Because the horizontal movements are the main interest, the 3-dimensional Cartesian coordinates were transformed into ellipsoidal coordinates, which were projected to plane coordinates using *Gauss-Krüger* projection. The conversion from ellipsoidal coordinates to plane coordinates was done using the GRS-80 ellipsoidal parameters. In order to minimize the projection errors the following central meridians were used in the projections: 21^{o} at Olkiluoto, 24^{o} at Kivetty and 27^{o} at Romuvaara.

5.3 Horizontal velocities

The components of the station velocities according to the permanent station (GPS1) were computed by linear regression from the plane coordinates obtained from the different sessions. The linear regressions were made separately for the N- and E-coordinates of the pillars.

At Olkiluoto we may notice some interesting features in the horizontal velocities. At five stations, viz. GPS2, GPS4, GPS7, GPS8 and GPS10 the east components exceed clearly the standard deviations of the determination. The negative sign of the component means that the pillars seem to move to the west with regard to the permanent station (GPS1).

At Kivetty the components of the horizontal velocities are so small that no movements can even be suspected during the observation period. The largest velocity component is 0.14 mm/y.

At Romuvaara we notice immediately the pillar GPS4, which seems to move eastwards. The velocity is approximately 0.3 mm/y, but the standard deviation of the determination is so large, 0.18 mm/y, that the result cannot be regarded statistically significant.

Because the statistically significant velocities were noticed only at Olkiluoto research area, we show those results in Table 2 and in Fig. 6.

Table 2. *Olkiluoto, the velocities of the GPS stations in mm/a with respect to the permanent GPS station. Observations 1995-2005, except station GPS10 (1995-2003).*

Station	North component		East component	
	Velo-city [mm/a]	St.dev. [mm/a]	Velo-City [mm/a]	St.dev. [mm/a]
GPS1	0.00	0.000	0.00	0.00
GPS2	0.04	0.04	**-0.20**	**0.04**
GPS3	0.05	0.06	-0.09	0.04
GPS4	0.12	0.05	**-0.25**	**0.02**
GPS5	-0.03	0.07	-0.02	0.04
GPS6	-0.03	0.04	-0.10	0.04
GPS7	**0.11**	**0.02**	**-0.09**	**0.03**
GPS8	0.08	0.03	**-0.21**	**0.04**
GPS9	**0.11**	**0.02**	-0.08	0.03
GPS10*	0.06	0.08	**-0.23**	**0.06**
RMS:		±0.05		±0.04

***** Observation period: 1995-2003

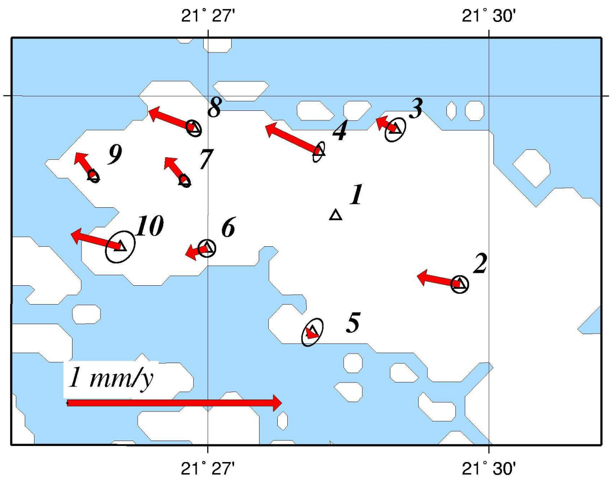

Fig. 6. *The velocities of the GPS-stations at Olkiluoto with respect to the permanent GPS station (1).*

6 EDM baseline at Olkiluoto

6.1 Background and establishment

The scale factors (Chap. 4.2) show that our GPS solutions may be significantly biased by scale errors. The systematic scale error is mainly caused by errors in ionosphere modeling. The scale factor varies between –0.3 and +0.3 ppm at Olkiluoto, but in 2002 at Romuvaara it was as large as +1.5 ppm.

FGI and Posiva decided to establish a baseline for electronic distance measurements (EDM) at Olkiluoto, in order to investigate the scale of GPS observations. According to maps and field survey there was only one GPS baseline, where it was possible to get visibility between two pillars. The distance between the pillars is about 511 meters and the height of the line of sight from the ground ranges between 2 and 8 meters.

6.2 Electronic distance measurement

Kern ME5000 mekometer is the most accurate EDM instrument, which is suitable for fieldwork. The mekometer of the Institute of Geodesy, Department of Surveying, Helsinki University of Technology was used. The mekometer was calibrated at the Nummela Standard Baseline at least once a year and the results are given in Certificates of Calibration of the National Standards Laboratory of the FGI.

The EDM baseline at Olkiluoto has been measured twice a year during the GPS measurement. Since 2002 we have observed the baseline 8 times simultaneously with the GPS observations.

The weather observations were made with calibrated instruments at the mekometer and at the reflector. Dry and wet temperatures have been observed with psychrometers and air pressure with aneroids.

6.3 EDM results

The results of the electronic distance measurements at the baseline GPS7-GPS8 are the means of observed distances after the first velocity corrections. In addition to the standard deviation, the standard uncertainty includes errors of centering and adjusting of instruments (± 0.1 mm), calibration of instruments (± 0.1 mm) and determination of refraction correction (± 0.1 mm).

The electronic distance measurements are traceable to the definition of the metre through the Nummela Standard Baseline. Last calibrations in Nummela have been performed in 2005 and interference measurements in 1996. Procedures meet the requirements of the standards ISO 9001 and ISO 17025. The results are given also in Certificates of Calibration of the National Standards Laboratory of the FGI.

The length of the baseline between the pillars GPS7 and GPS8 obtained by GPS and EDM in different sessions is shown in Fig. 7. The systematic difference between GPS and EDM determinations is seen immediately. The EDM results are appr. 0.6 mm shorter than those obtained by GPS. The first explanation of the systematic difference is that the phase centres of the GPS antennas does not coincide with the centring markers of the EDM instruments. This was tested by changing the pillars of the GPS antennas between two 24 hours sessions, but no explanation was found. The EDM determinations will be continued simultaneously with the GPS measurements.

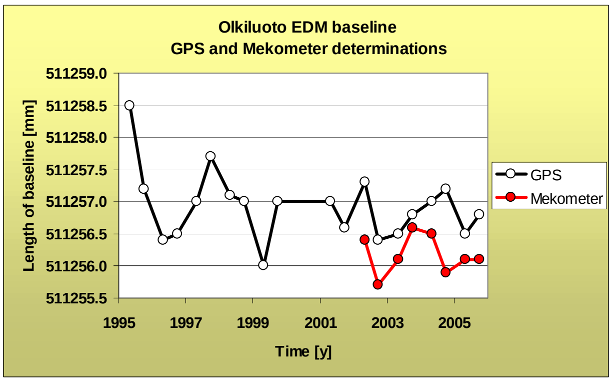

Fig. 7. *The GPS and EDM results.*

7 Conclusion

The analysis of the GPS data shows that all investigation areas are stable as expected. Most of the baselines (about 97 %) have change rates, which are less than 0.2 mm/a. However, looking at the horizontal velocities at the Olkiluoto investigation area, shows interesting pattern of the velocities. The local velocity components are small but taking into account the standard deviations the largest velocity components seems to be reliable (maximum velocity is - 0.25 mm/a ± 0.025 mm/a).

Taking into account the magnitude of the largest change rates found, we may conclude that the bedrock at all research areas have been stable during the short observation span.

The change rates observed at the research areas are, however, so small that they just exceed the accuracy of the GPS observations. In order to get more reliable results the time span of the observations should be longer, i.e. the determination of the baseline lengths should be repeated in coming years. GPS observations made until now form a good basis for further investigations of the deformations on the investigation areas.

Acknowledgements

This work has been carried out in co-operation with the Posiva Oy. The expenses caused by the field observations were mainly funded by Posiva Oy. The authors are acknowledged for the good co-operation with Posiva Oy.

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Repeated absolute gravity measurements across the Roer Graben to infer tectonic deformation

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Over the last 10 years, space geodesy has been providing data for the study of crustal movements in Europe and elsewhere. Considering the importance of measuring present-day crustal deformations for the interpretation of the character of the seismotectonics in the Lower Rhine Embayment, the Royal Observatory undertook a profile of absolute gravity (AG) measurements across the Ardenne and the Roer Graben to infer vertical crustal movements in these two regions. This eight-station profile is 140 km long and measurements are performed twice a year. It should allow one to detect the spatial extension of the uplift expected from the tectonic activity but also to discriminate it from long-wavelength phenomena like post-glacial rebound.

The first results of the profile already indicate that there is no detectable movement corresponding to gravity changes higher than 1.3 µGal/yr at a 2 level. This is equivalent to approximately 6.5 mm/yr of vertical movement. Taking into account the free air and Bouguer corrections, 5 mm of uplift reduces the value of gravity by about 1 µGal. Repeated AG campaigns should allow one to constrain a gravity rate of change with an uncertainty of 1 nm/s² (or 0.5 mm of vertical movement) after 15-25 years.

A new interferometrically recording water level tilt meter

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Abstract

A new prototype of the water level tilt meter follows the ideas given by Michelson & Gale 1919, Kukkamäki 1964 and Kääriäinen 1979. Fizeau type interferometer is used for water level sensing and it seems to be stable for long term geodynamical recordings. The instrument is fully automatic, easy to install and computer controlled via intranet/internet. High thermal stability of installation site is necessary for elimination of signals caused by thermal expansion of the tube, end pots and fluid.
Reliable interpretation of earthquakes and microseismic events is essential in crustal deformation studies.

A new prototype of the water level tilt meter

Fig. 1. shows setup of the tilt meter at the Finnish Geodetic Institute (FGI) laboratory.

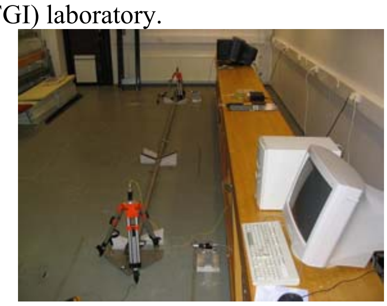

Fig. 1. *Setup of the water level tilt meter at the laboratory of FGI (Photo: H. Ruotsalainen)*

Main parts of the instrument are a stainless steel tube (length ~5.5m, inner diameter 50 mm) half filled with water, end pots on tripods, fibre-optics with HeNe-laser, CMOS-cameras and computers in the network. The cover plate system of the pot is one of wedge glass in 45 degree angle and in the same angle another glass window through which the fringes are reflected to the camera. Fig. 2. shows details of the end pot construction. In Fig. 1. between computers in the middle of the table there is a HeNe-laser with a fibre-optic coupler system for interferometer.

Fizeau thin film interferometer for fluid level sensing

Michelson type open-air interferometer (Michelson & Gale, 1919) is sensitive on thermal modulation because optical arm lengths may vary with the thermal expansion and/or because of changes in air temperature and pressure (Agnew, 1986), (Ruotsalainen, 2001b). The Fizeau-type thin film interferometer seems not to suffer from such a modulation and is therefore more suitable for long term fluid level recording (Ruotsalainen, 2005). Our laser system consists of JDS Uniphase HeNe laser (λ = 543nm) with OFR PAF-XM_5_VIS fiber port connected to single mode fibres and a coupler. Thereafter the beams are transferred to the telescope type collimators using single mode fibres. Interferences are formed with a convex-plane lens immersed slightly below the water surface in each end pot. Interference fringes are detected by using computer controlled CMOS IEEE1394-type cameras. System clocks of the computers are stabilized by using Network Time Protocol (NTP) time servers.

Fig. 2. *End pot construction on the tripod plate.*

Test recordings and their interpretation

Fringe analysis program run parallel with fringe recording cameras under Linux (Fedora 5.0) operating system. The recording and analysis program are fully controlled via intranet/internet. Fig. 3. shows preliminary recordings of the tilt meter carried out at the FGI laboratory.

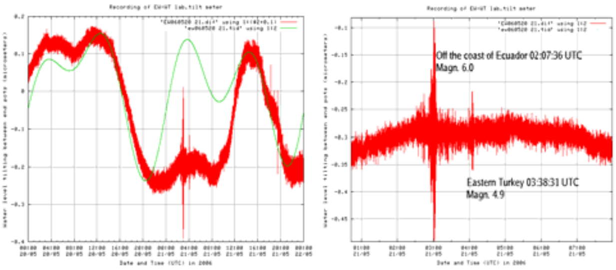

Fig. 3. *Crustal tilt recording with the new tilt meter in 20. –21.05.2006 and the right side figure is a detailed picture of the two earthquakes in 21.05.2006.*

We have developed and tested least squares adjustment routines for more precise determination of phases within interferograms. In Fig. 3. we see the observed crustal tilt (thick curve, scale ~ +-0.2 µm/5.5m base) with the theoretical model tilt (thin curve) (Heikkinen, 1978). In two days recording the amplitude of microseismic background noise is about 50 nm. Earthquakes may cause fringe phase interpretation errors, which is seen as deviations from theoretical model. The earthquake section is enlarged in the right side picture, where exists one earthquake in off the coast of Equador (magn. 6.0) and another in Eastern Turkey (magn. 4.9). Reliable interpretation of earthquakes and microseismic events is essential for analysis of high precision geodynamical time series.

A suitable tilt meter for crustal dynamics research

The instrument can be used for all kind of crustal tilt research like Earth Tides, ocean and atmospheric loading and tectonic movements. The tilt meter has absolute scale and continuous recording, which is not always the case with other high precision geodetic instruments. Following Michelson & Gale principles (1919), instrument must be as simple as possible for detection of micrometer – nanometer level geodynamic signals.

Conclusions

Instrumental stability is essential for geodynamical research. Water tube tilt meter has simple design and Fizeau interferometer is precise fluid level sensor. Thermal stability is important and seismic and microseismic events must be interpreted carefully to improve the quality of time series.

Acknowledgement

I thank Mr. A. Pavenis, who programmed the main sections of the tilt meter software in 2005.

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Analysis of GRACE, Superconducting Gravimeter and Water Storage Time Series

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In the past few years, knowledge of the time varying part of the gravity field has improved due to the contributions from superconducting gravimeters and the GRACE satellite mission. Here, the time series from GRACE and from the superconducting gravimeter in Metsähovi are analysed and compared with time series from water storage models over Finland.

Two water storage models are used: The high accurate daily model for Finland, the Watershed Simulation and Forecasting System (WSFS), and The Climate Prediction Center global soil moisture monthly data set (CPC). The CPC correlates well with the WSFS. In addition local data such as precipitation, snow cover and ground water level, are available for the Metsähovi station.

For comparison with the GRACE data, the effect of the local groundwater should be reduced from the superconducting gravity time series. However, local groundwater is strongly correlated with the regional water storage and it is therefore difficult to separate the near-field water storage attraction from the loading effect of the regional water storage.

Time series of absolute gravity in Finland

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The Finnish Geodetic Institute has repeated absolute gravity measurements in Finland at three sites since 1988, and shorter time series are available at additional stations. Initially the JILAg-5 instrument was used. Since 2003 the work is continued with the FG5-221. In addition, we use individual observations by IMGC (1976), ANSSSR (1980), NOAA (1993, 1995), BKG (2000, 2004) and IfE (2003-). Vertical velocities due to postglacial rebound (PGR) at the stations, observed with a multitude of techniques, are up to 1 cm/yr. Gravity results are consistent with a ratio of approximately -2 μGal in gravity per 1 cm uplift.

The Fennoscandian Land Uplift Gravity Lines 1966–2005

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The Fennoscandian Land Uplift Gravity Lines consist of four east-west profiles across the Fennoscandian postglacial rebound area, along the approximate latitudes 65º, 63º, 61º, and 56ºN. Repeated relative gravity measurements have been so far performed 1975–2000 (65ºN), 1966–2003 (63ºN), 1976–1983 (61ºN), and 1977–2003 (56ºN). The line 63ºN has most observations. From the measurements along it up to 1993, Ekman and Mäkinen (1996) deduced the ratio –0.20 µgal/mm between surface gravity change and uplift relative to the Earth's center of mass. Since that time, more gravity measurements have been made. On the eastern part of the line 63ºN, they result in slightly smaller estimates for the rate of gravity. New estimates of uplift and model predictions are also available. The updated gravity change combined with various estimates of uplift gives ratios between –0.16 and –0.20 µgal/mm. On the western part of the line 63ºN an apparently anomalous change in gravity difference is so far unresolved. In 2003-2005 measurements on the line 63ºN were continued using absolute gravity techniques.

Remeasurement of the Icelandic reference network (Abstract)

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The Icelandic reference network was measured with GPS in August 1993. The network replaced the Hjörsey55 datum, which was unusable because of deformation, due to plate tectonics, and inaccessibility. In this campaign Icelanders got very generous support from IfAG and IfE. The results were ready in 1996 and the estimated accuracy was 10 mm in plane and 20-30mm in height.

Maintaining precise geodetic network in Iceland is not an easy task. The main reason is the geodynamics of Iceland. The country is slowly drifting apart due to its position on the Mid-Atlantic ridge at the boundaries of the North-American and Eurasian plate. This combined with deep-seated mantel plume positioned under Vatnajökull provides complicated systems of rift and transform fault zones. This leads to volcanic and seismic activities in Iceland. It means that the whole reference network is slowly but constantly deforming due to plate tectonics and local deformation can occur because of volcanic or seismic events. Therefore the reference network has to be remeasured regularly.

The ISN93 network was remeasured in August 2004. The campaign was planned and carried out by Icelandic institution and municipalities. This is the first campaign of this magnitude that Icelanders plan and carry out by themselves.

The data from the campaign was processed with three different types of software Trimble Total Control, GEONAP and Bernese. The final solution is a combination of the three software solutions. The estimated accuracy is considerably better than the 1993 measurements or around 5mm in plane and 10mm in height. When the results are compared with the 1993 results changes are seen in both plane and in height. Movement in plane seems to follow the pattern of the rift zones as expected. Points west of the plate boundaries are moving to the northwest and points east of the plate boundaries are moving to the northeast. The magnitude of the point movements in plane is up to 30 cm. Land uplift seems to occur mostly around Vatnajökull in Mid-Iceland and along the Northern rift zone but land subsidence seems to occur mainly along the west coast of the country. The magnitude of height changes is up to 20 cm.

Continuous GPS observations and absolute gravity network in Dronning Maud Land, Antarctica

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The solid Earth is deformed by present and past changes of the ice mass. Continuous GPS (CGPS) senses the deformation. Repeated absolute gravity is sensitive to the vertical component of the deformation. It is also sensitive to the associated variation in density of the solid Earth, and to the direct attraction of the ice mass. Additional insights into the processes at hand can thus be gained by combining the two types of observations.

Finnish Geodetic Institute maintains a program of repeated absolute gravity and CGPS in Dronning Maud Land. In 2003 a CGPS receiver was installed at the Finnish Antarctic Research Station Aboa (73º03' S, 13º24' W). It has so far collected three years of uninterrupted data at this summer-only base.

In 1994 FGI made the first absolute gravity measurement at the Aboa. The measurement was repeated in 2001. In 2004 the gravity project was extended to the South African station Sanae IV (which is the International GPS Service site VESL) and at the Russian station Novolazarevskaya. During the field season 2005-2006 we repeated the gravity measurements at Aboa, Sanae IV, and Novolazarevskaya. All work is performed under the auspices of the Finnish Antarctic Research Program FINNARP.

We describe the work, show the results obtained so far, and discuss the key phenomena present in the time-variable gravity signal and in the CGPS.

BIFROST: A New and Improved Velocity Field for Fennoscandia - Implications for models of Glacial Isostatic Adjustment

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(3) Swedish National Testing and research Institute.
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Introduction

The BIFROST (Baseline Inferences for Fennoscandian Rebound Observations Sea Level and Tectonicas) project was started in 1993. The first primary goal was to establish a new and useful three-dimensional measurement of the movements in the earth crust, able to constrain models of the GIA (glacial isostatic adjustment) process in Fennoscandia. Data from permanent GNSS-stations are analyzed on a daily basis in order to retrieve station velocities. These velocities have then been used to constrain a visco-elastic self-graviting model of the Fennoscandian GIA process.

GPS analysis

We use the GAMIT/GLOBK and the GIPSY/OASIS II software packages for analysis of the GPS data.

The analysis using GAMIT is performed as a network analysis where the regional analysis is combined with global products from SOPAC. The combination, which apply orbit relaxation, result in daily solutions in a defined reference frame (ITRF2000) using a selection of 44 globally well distributed stations.

In the GIPSY analysis we apply the PPP (precise point

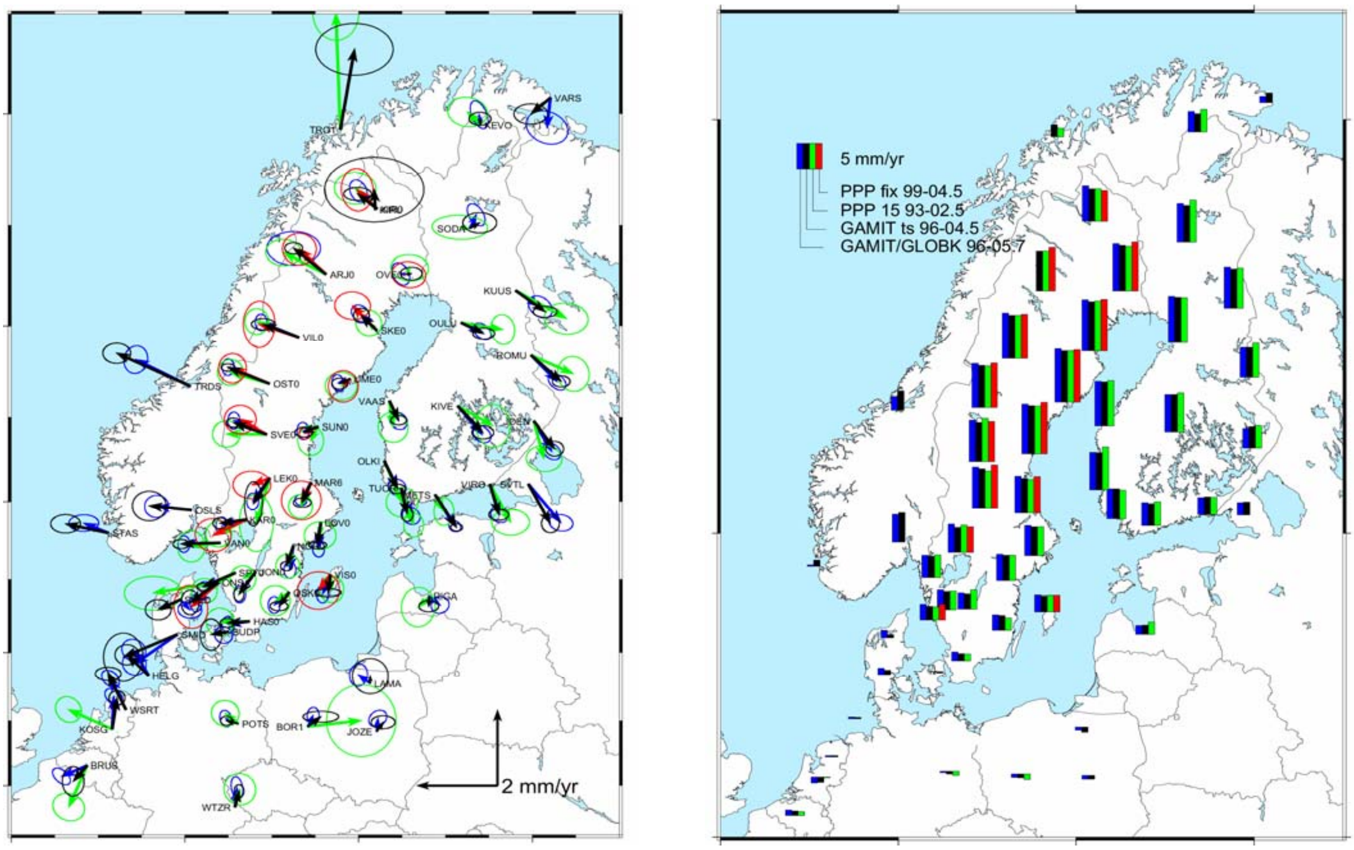

Figure 1. Comparison of horizontal (left) and vertical (right) velocities from four different GPS solutions, see text.

positioning) strategy using the no-fiducial products from JPL. The no-fiducial solutions are given a defined reference frame in the completing daily transformations. In the analysis where we also fix the phase ambiguities to integers the result is a network solution, however with the same reference frame realization and similar CMV (common mode variation) behaviour as the traditional PPP solution. Comparisons between the four solutions are found in figure 1 and table 1.

Black: GAMIT 1996-2004.5. Velocities derived using time series analysis including model for seasonal variations. This solution is described in Lidberg et al (2006) and used as reference for further analysis.

Green: GIPSY PPP (precise point positioning) 1993-2002.5. Products (clocks, orbits etc) from JPL. Velocities from time series as above.

Red: GIPSY PPP ambiguity fix 1999-2004.5. Velocities from time series as above.

Blue: GAMIT 1996-2005.7. Velocities derived in the GLOBK analysis (assuming Gauss-Markov process).

Table 1. Three recent preliminary GPS velocity solution compared to the GAMIT 1996-2004.5 solution (see text).

GPS solution	horizontal	vertical	
Unit: mm/yr	Std	mean	Std
GIPSY PPP	0.29	0.14	0.45
GIPSY amb. Fix	0.21	0.37	0.30
GAMIT/GLOBK vel.	0.22	0.20	0.46

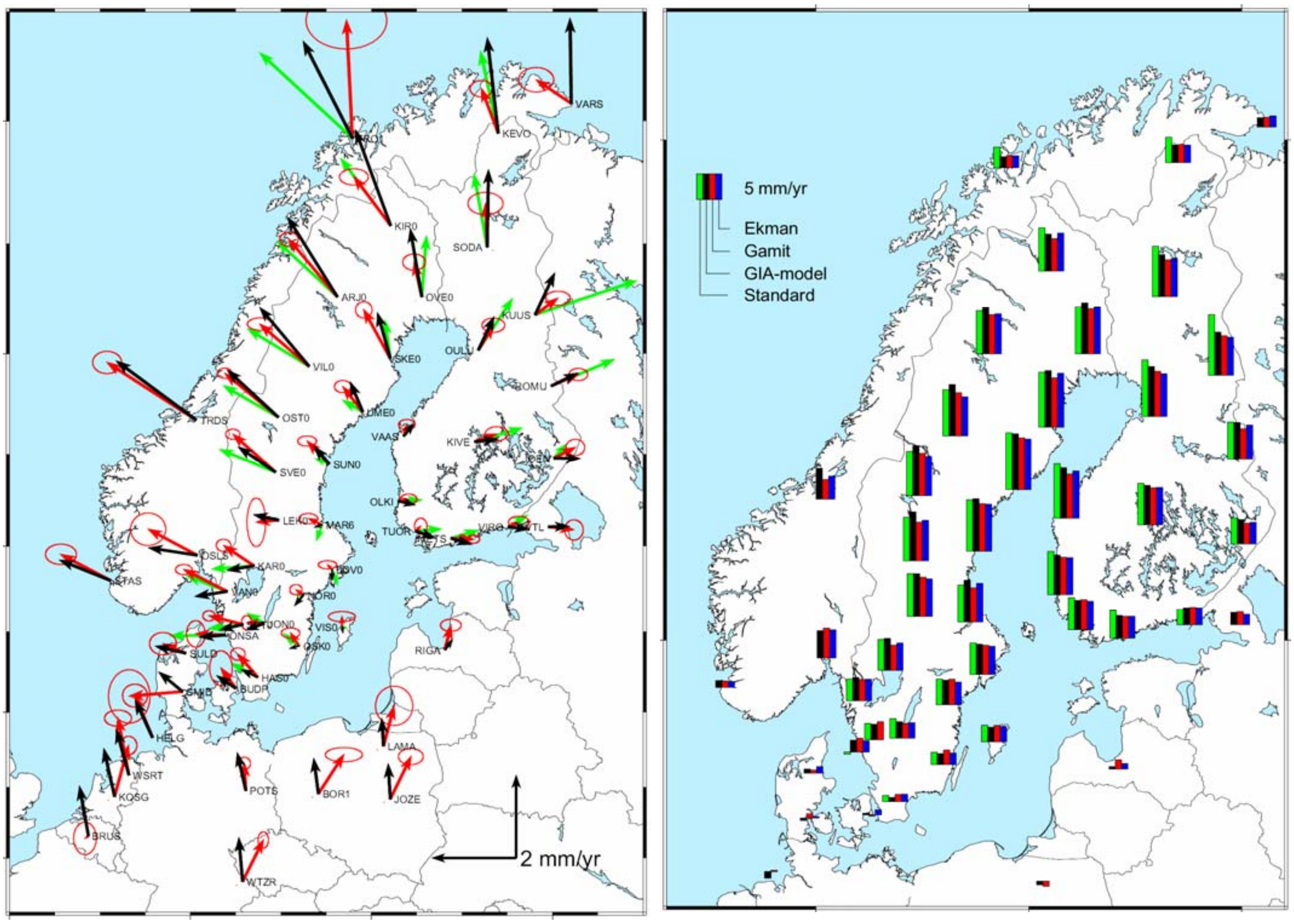

Figure 2. Comparison of horizontal (left) and vertical (right) velocities from four different GPS solutions, see text.

Comparison to previous published values

In figure 2, the GAMIT 1996-2004.5 reference solution (red with error ellipses) are compared to the previous published BIFROST solution (Johansson et al. 2002) in green without error ellipses. In black we have the GIA prediction model (Milne et al. 2001) using ice history from (Lambeck at al. 1998a,b), derived 120 km lithosphere, upper and lower mantle viscosity of 0.8 and 10x1021 Pas resp.

In **blue** we have the estimates of vertical rates by Ekman (1998), based on mareographs and levelling, sea level rise of

1.2 mm/yr and rise of the geoid from Ekman & Mäkinen (1998).

Table 2. The previously published BIFROST solution, GIA model predictions, and values derived from classic geodetic observation compared to the GAMIT 1996-2004.5 solution (see text).

Velocity estimate	horizontal	vertical	
Unit: mm/yr	Std	mean	Std
GIPSY (JGR 2002)	0.4	0.8	1.2
GIA model prediction	0.5	0.3	0.9
Ekman (1998).		0.1	0.5

Conclusions on GPS derived station velocities

From different solutions using in total >12 yr of continuous GPS data we get agreement in station velocities at the few 0.1 mm/yr.

We see indication of a bias in the vertical rate between GAMIT and late GIPSY solutions at the 0.4 mm/yr level, which is not eliminated by analysing identical time-spans. Instead, we argue that differences in reference frame realisations may cause this bias.

The current GIA prediction model (2001) gives on the average larger station velocities compared to the new GPS velocities.

The GIA model fit the new GPS solution better than the BIFROST JGR (2002) solution, which the GIA model is tuned to. Better, especially more homogeneous data quality may be the reason.

Coloured noise in GPS time series

The presence of non-white noise in GPS position time series has the effect of too optimistic velocity uncertainties if a white noise model is assumed. The noise may be characterised by its spectral index, which can be seen as the slope of power-spectra of the noise when plotted in a log-log diagram.

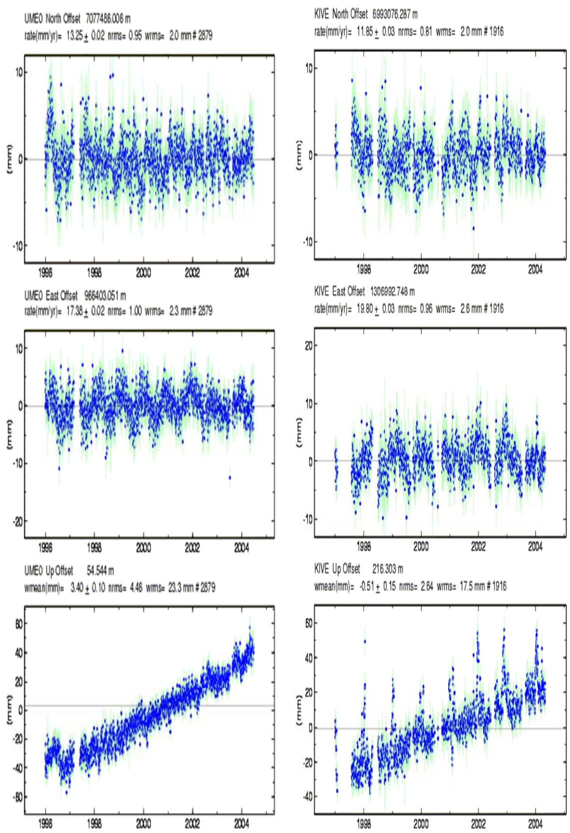

Figure 3. Example of time series of 8.5 yr (3100 days) of daily position estimates. Umeå to the left and Kivetty to the right. Note the seasonal variation for Umeå and vertical outliers at Kivetty.

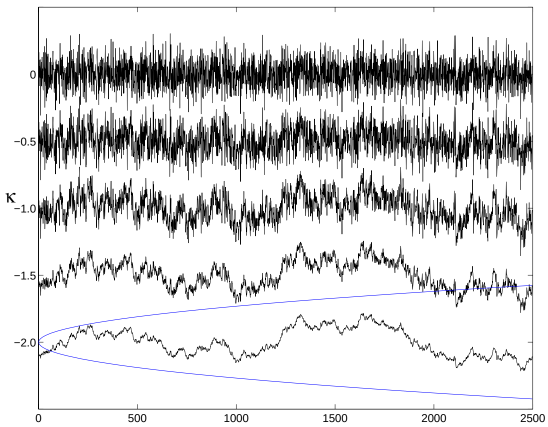

Figure 4. 2500 days time series of synthetic noise simulated with different fractal power law parameters.

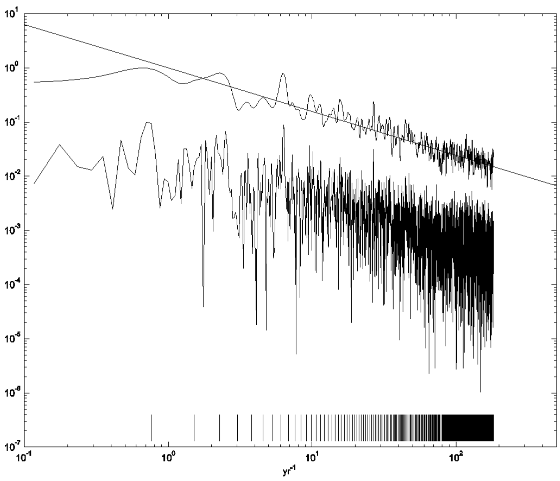

Figure 5. Power spectra of vertical time series for SUND (Sundsvall, Sweden) from the GAMIT reference solution. Note the spectral index of about 0.8. Also, a high-frequency noise floor is not visible up to 2 cyc/d.

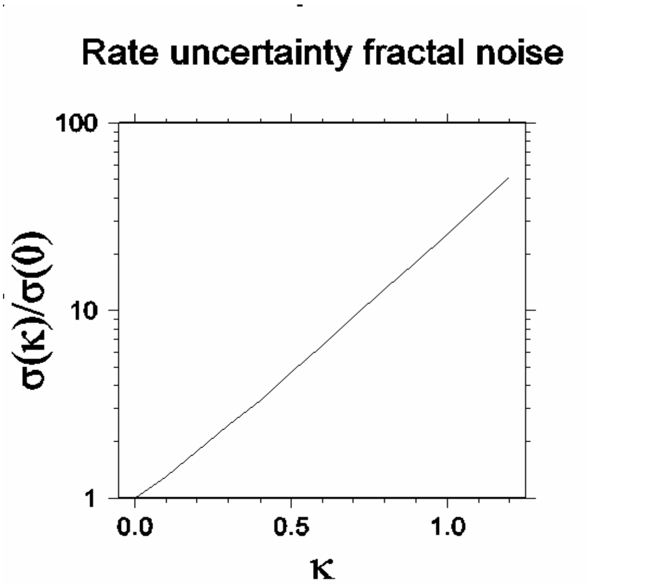

Figure 6. The rate uncertainties derived using a white noise model should be multiplied by about 12 when the spectral index is 0.8.

Ice and Ocean Load

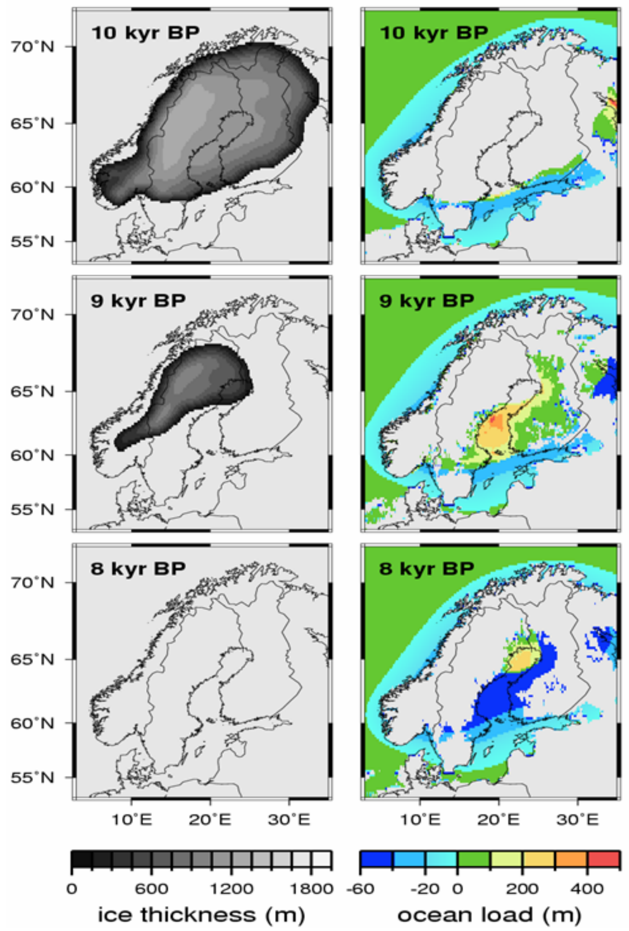

Figure 7. Ice and ocean load at three stages of deglaciation.

The glaciation maximum of the Pleistocene occurred ~18 kyr ago. Shown in figure 7 are three later stages of deglaciation at 10, 9 and 8 kyr before present. The right column shows the change of the accompanying ocean load. The receding ice edge and the increasing sea level cause the ocean load to increase while the land uplift displaces sea water outward from the rebound area. The load model is fully consistent with a rotating visco-elastic, self-gravitating and land-ocean-covered planet.

Updated GIA prediction model

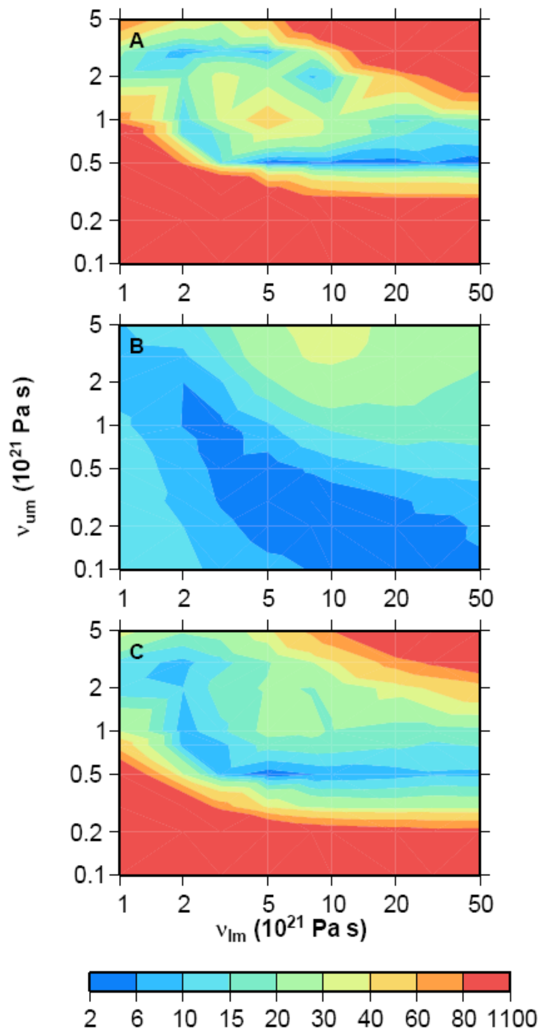

Figure 8. $\chi 2$ misfit per degree of freedom (d.o.f) between GPS-derived crustal velocities and numerical GIA predictions based on a suite of Earth models. See text.

The new GPS rates have been used to determine a revised viscosity model. For a given ice load model (Lambeck 1998) the new GPS solution is best fit by a viscosity model with values in the upper and lower mantle that are less than those found in (Milne et al. 2001).

The $\chi 2$ misfit per degree of freedom (d.o.f) between GPS-derived crustal velocities and numerical GIA predictions based on a suite of Earth models are shown in figure 8. Misfit is shown as a function of vum and vlm (upper and lower mantle viscosity) for the (A) radial,

(B) horizontal, and

(C) full 3D velocity components, respectively.

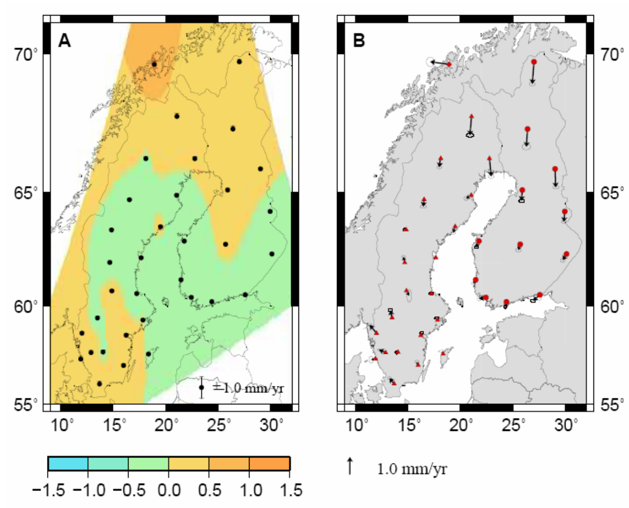

Figure 9. Residuals in vertical (left) and horizontal rates (right), determined by subtracting predictions obtained by the best fit model from the observations.

Summary and outlook

BIFROST is a continuous effort where much work is going on for the moment. In this paper is presented new and highly improved station velocity values from preliminary processing results. More complete results will be presented in the near future.

Currently the methodology of GPS processing is in a phase of intensive research. The transition from relative calibrated values of GPS receiver and satellite antennas to absolute values within IGS are expected in the near future (Schmidt et al 2004). Site dependent effects in BIFROST have been studied in e.g. Granström (2006). Higher order ionospheric effects have also an effect on estimated positions (Kedar et al. 2003). Implementation of this in scientific GPS software packages are going on or are under investigation, but seems to be more complicated than the transition of antenna models. Updated models for solid earth-tide and ocean loading as well as implementation of atmospheric loading corrections have also been developed and investigated recently (e.g Tregoning and van Dam 2005, and Watson et al. 2006).

We hope to be able to implement these recent findings the the BIFROST analysis in the near future. However, in a research effort like BIFROST we are very much dependent on products from the IGS or some of its analysis centres (so far especially JPL and SOPAC). Therefore the implementation may not be as immediate as we could hope for. With the evolution in computation capacity this situation may be changed in the future.

Error analysis of GPS time series has been a field on intensive research recently (e.g. Williams et al. 2004). Of special interest for BIFROST is its influence on reliable estimation of uncertainty in derived station velocities. An extensive analysis using BIFROST data can be found in Bergstrand et al (2005).

A first test of updating the GIA prediction model has also been conducted. It shows that the new station velocities are more homogeneous compare to previous published values. Including further improved station velocities and stations in the outer area of the Fennoscandia GIA area are expected to improve the modelling and also extend the area of validity of the GIA model. The later is important if the model will be implemented to account for earth crust deformation in geodetic coordinate transformation algorithms (e.g. Lidberg and Johansson 2005).

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Geodetic VLBI in Northern Europe – Status and Vision

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Introduction

Currently four stations in Northern Europe are active in geodetic VLBI: Onsala, Ny-Ålesund, Svetloe and Metsähovi. These stations participate regularly in the observing sessions organized by the International VLBI Service for Geodesy and Astrometry (IVS) (Schlüter *et al.*, 2002). Due to their northern location they are important for earth rotation observations, in particular polar motion determination, and the maintenance of the international terrestrial reference frame (ITRF) (Altamimi *et al.*, 2002). The four stations are located at the periphery of the region in Fennoscandia that is affected by glacial isostatic adjustment (GIA) processes. Thus, baselines measurements between these stations and to station in Central Europe can give insight about the deformation of the area, as an independent complement to results obtained by Global Navigation Satellite Systems (GNSS) (e.g. Johansson *et al.*, 2002).

The geodetic VLBI technique undergoes currently a technical evolution that aims at a significant increase in accuracy of the technique. Since several months the IVS systems committee discusses recommendations for the VLBI2010 initiative (Niell *et al.*, 2005). New radio telescopes with faster azimuth and elevation drives, extended frequency bands, broad-band phase-delay solutions and the use of e-VLBI are discussed. Already today most of the stations in Northern Europe are connected to the international high-speed optical-fibre backbone networks and thus prepared for e-VLBI, i.e. the transfer of VLBI observational data via optical fibre.

In the following, the current status of geodetic VLBI in northern Europe is briefly described and some results from observations involving the geodetic VLBI stations in Northern Europe are presented. This is followed by a vision on the development of geodetic VLBI in Northern Europe.

Fig. 1. VLBI stations in Northern and Central Europe currently used for geodetic and astronomical VLBI observations, marked by red dots and red triangles, respectively. The active geodetic stations in Northern Europe are shown with black names.

Status

Figure 1 shows the locations of geodetic and astronomical VLBI stations in Northern and Central Europe, marked by red dots and red triangles, respectively. The active geodetic stations in Northern Europe are indicated with black names. The network covers the global isostatic adjustment (GIA) area in Northern Europe.

The geodetic stations are actively participating in the observing sessions organized by IVS and thus contribute to earth rotation observations and the maintenance of the ITRF.

Two examples of VLBI results involving the stations in Northern Europe are presented briefly in the following:

a) High-frequency earth rotation parameter (ERP) variations observed during the continuous VLBI campaign CONT05.

b) Baseline length measurements in Europe.

High-frequency ERP variations observed in the CONT05 campaign

The IVS organizes every couple of years continuous VLBI campaigns that last several days and involve global VLBI networks. The Northern stations Onsala, Ny-Ålesund and Svetloe participated in the continuous campaign in September 2005, CONT05. The CONT05 network involved both long north-south and long east-west baselines, i.e. it was very sensitive to Earth rotation parameter (ERP) variations. Figure 2 shows polar motion and UT1 variations from CONT05 with a temporal resolution of 1 hour as black dots with error bars (Haas, 2006), together with model predictions based on oceanic angular momentum (Ray et al., 1994; IERS, 2003) as red continuous lines. Figure 3 shows the corresponding amplitude spectra (Hocke, 1998; Press et al., 1992) of the differences between the CONT05 ERP observations and the model predictions. Significance levels of 99.5%, 95% and 50% are given as horizontal dashed lines. Clearly, significant peaks in the diurnal and semi-diurnal frequency bands are visible, which need to be investigated in more detail.

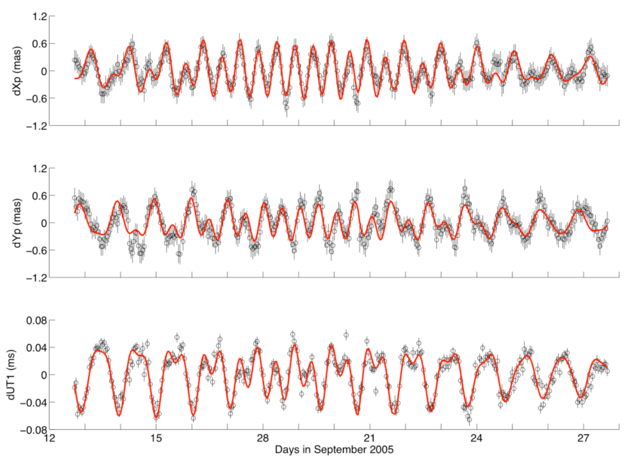

Fig. 2. Polar motion and UT1 results from CONT05 (Haas, 2006) with a temporal resolution of 1 hour (black dots with error bars). Corresponding model predictions for high-frequency ERP variations (Ray *et al.*, 1994; IERS, 2003) are shown as red continuous line.

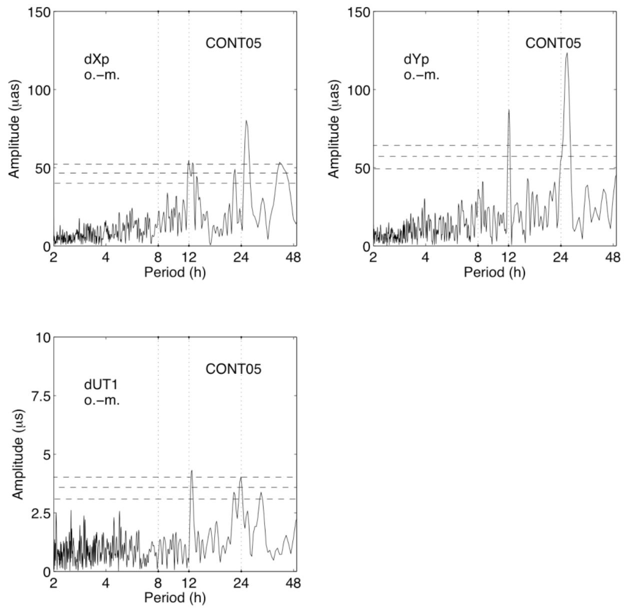

Fig. 3. Amplitude spectra (Hocke, 1988, Press *et al.*, 1992) of CONT05 ERP residuals, i.e. observations minus model predictions (Ray *et al.*, 1994, IERS, 2003)**.** Show are polar motion (upper row) and UT1 spectra together with horizontal dashed lines indicating top to bottom the significance levels 99.5%,95% and 50%, respectively.

Baseline length measurements in Europe

The four geodetic VLBI stations in Northern Europe are located at the periphery of the region in Fennoscandia that is affected by glacial isostatic adjustment (GIA) processes. Baselines measurements between these stations give an independent complement to Global Navigation Satellite System (GNSS) results on crustal deformation in this region. Measurements connecting to stations in Central Europe give in particular information about the deformation in the forebulge area. Table 1 lists baseline length rates from VLBI together with corresponding model predictions. Significant discrepancies can be detected and need to be investigated further. Figure 4 shows some baseline length observation from VLBI (Nothnagel and Vennebusch, 2006) between stations in Northern and Central Europe.

Table 1. Baseline rates from geodetic VLBI (Nothnagel and Vennebusch, 2006) and GIA model (Milne *et al.*, 2001). All values are given in units mm/yr.

baseline	VLBI	Model
Onsala – Ny-Ålesund	+1.74 ± 0.14	+2.93
Onsala – Svetloe	+1.86 ± 0.40	+0.96
Onsala – Metsähovi	–	+0.86
Onsala – Wettzell	–0.67 ± 0.04	–1.54
Ny-Ålesund – Svetloe	+3.54 ± 0.77	+2.68
Ny-Ålesund – Metsähovi	–	+3.40
Ny-Ålesund – Wettzell	+0.97 ± 0.06	+0.66

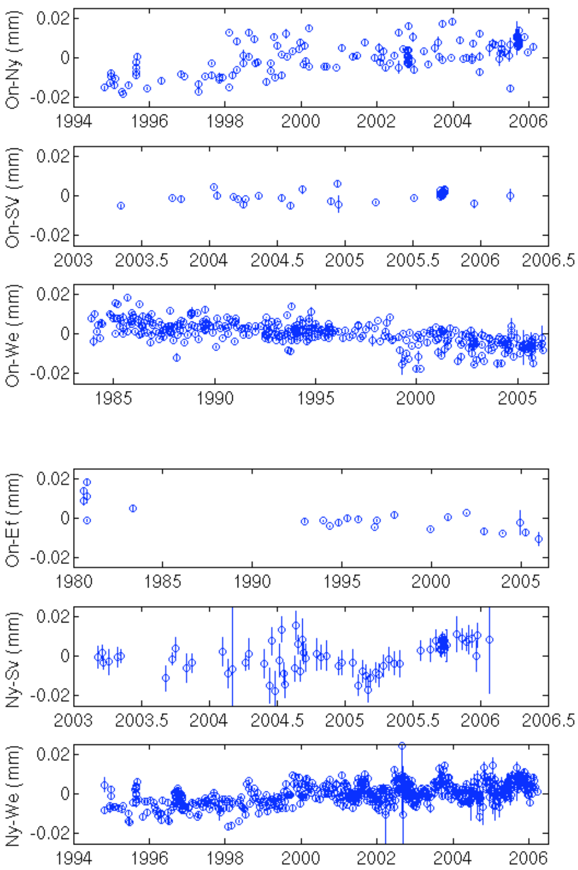

Fig. 4. Baseline length observations from geodetic VLBI (Nothnagel and Vennebusch, 2006). Shown are some of the baselines between the three stations Onsala, Ny-Ålesund and Svetloe in Northern Europe, and the two stations Wettzell and Effelsberg in Central Europe. Since there are so far only a small number of measurements with Metsähovi, these results are not shown here. Average baseline length values are subtracted and only the remaining residuals in mm are presented.

Vision

The geodetic VLBI technique undergoes currently a technical evolution that aims at a significant increase in accuracy of the technique (VLBI2010 initiative, Niell *et al.*, 2005). Among other ideas extended frequency bands, phase-delay solutions and the use of e-VLBI are discussed. The VLBI stations in Northern Europe should be fully compatible with the future VLBI2010 system.

Already today most of the VLBI stations in Northern Europe are connected to the international high-speed optical-fibre backbone networks and thus well prepared for e-VLBI, i.e. the transport of VLBI observational data via optical fibre. The connectivity of Ny-Ålesund, Onsala and Metsähovi are currently 80 Mbps, 1 Gbps and 10 Gbps, respectively. Further increase in data rate capacity is planned.

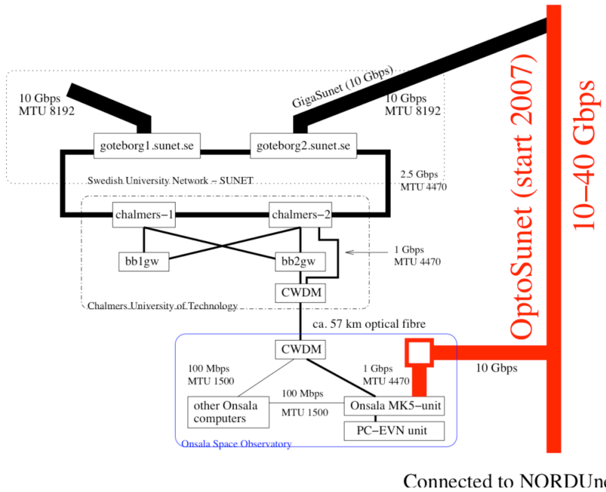

Fig. 5. Black: Current netwok configuration (1 Gbps connection) between the Onsala VLBI data acquisition system and the Swedish University Network (SUNET). Red: Future network configuration (10 Gbps) active most probably in early 2007.

Figure 5 shows the current and future network connection of Onsala and Figure 6 shows the first real-time fringe plot with 512 Mbps on the inter-continental baseline between Onsala and Westford, achieved in autumn 2005.

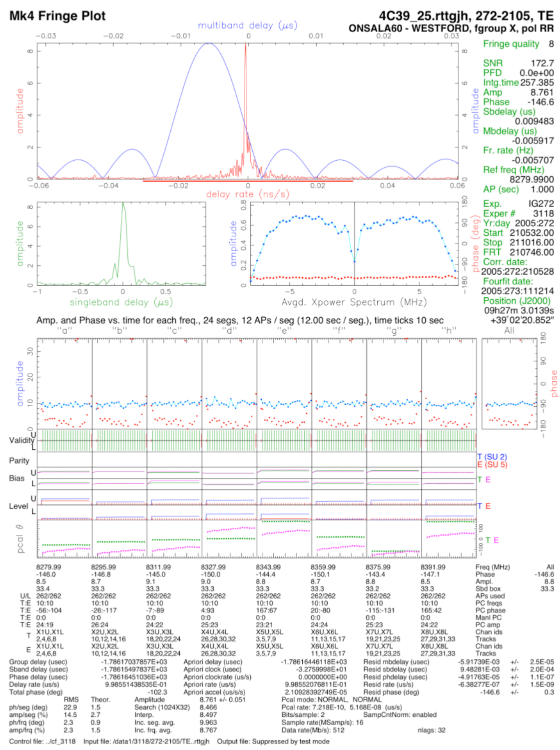

Fig. 6. Fringe-plot of the first real-time transatlantic correlation at 512 Mbps between Onsala and Westford, correlated at Haystack in autumn 2005.

During the NKG General Assembly 2006 in Copenhagen a NKG VLBI Task Force was initiated to coordinate the geodetic VLBI activities in the Northern countries.

A continued and extended participation in the IVS observing schedule will be aimed at. In particular it appears worthwhile to increase the number of Nordic VLBI sessions sessions for GIA studies as contribution to the Nordic Geodetic Observing System (NGOS). Furthermore, the possible inclusion of astronomical VLBI stations that are located in the GIA forebulge area into geodetic VLBI observing sessions will be investigated.

For the future a general aim is to use the optical fibre connections regularly for e-VLBI data transfer. Most of the geodetic VLBI sessions that involve the stations in Northern Europe are correlated at the Bonn correlator. This correlator is currently is upgrading its network connection and network connection tests with Onsala are ongoing.

An interesting idea is to combine e-VLBI data transfer with software correlation. Contacts with Japanese colleagues have been established to use the Japanese software correlator during 2007 for some special observing sessions. The idea is to perform intensive UT1-observations on two almost parallel baselines between Europe (Onsala and Metsähovi) and Japan (Kashima and Tsukuba) (see Figure 7) with e-VLBI data transfer and software correlation.

The compatibility with VLBI2010 means that the VLBI stations probably need to be upgraded to be able to observe a wider frequency range. New broadband feed-horns covering 2-15 GHZ or 2-18 GHz are discussed in the IVS systems committee. New strategies shall allow to do phase-delays solutions that promise higher measurement accuracy than today’s group delay solutions.

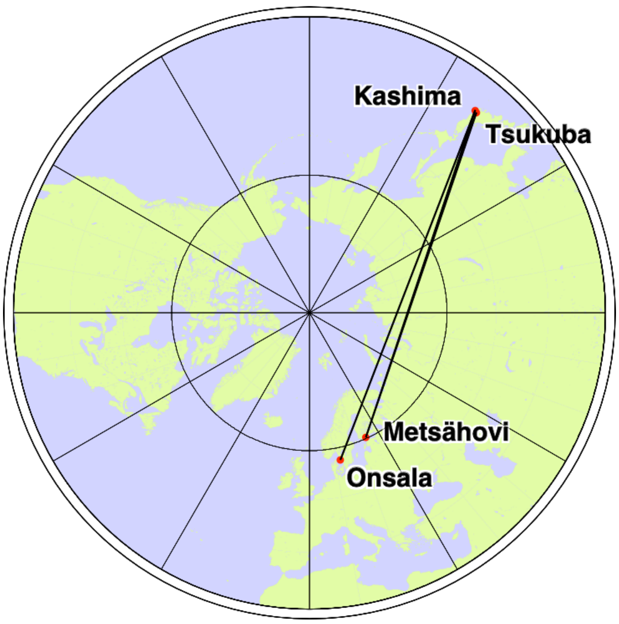

Fig. 7. Proposed network for UT1-intensive measurements on two almost parallel baselines between Europe and Japan, using e-VLBI and software correlation.

The IVS systems committee currently discusses telescopes with a diameter of 12 m and fast telescope drives that allow movements of up to 9 degrees per minute. Therefore, some of the VLBI stations in Northern Europe might even plan to construct new faster telescopes.

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Environmental loading effects on GPS time series

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Loading of the Earth's crust is a multiform phenomenon. In Finland the effect of the ocean tide loading is small and therefore we are able to see other loading factors more clearly in the time series of a permanent GPS station, Metsähovi. A superconducting gravimeter (SG) is also located in Metsähovi and we can use the synergy of the SG and GPS at the same time to separate the loading from different sources. In the radial component of the GPS time series we have found loading caused by air pressure, non-tidal changes in the Baltic Sea and different models of water storages. The range of the vertical motion in Metsähovi is 38 mm. We used regression methods and loading calculations based on Green's functions to see the effects of different phenomena. The variance of the GPS time series diminishes up to 30 % when all the different factors are taken into account. With shorter time series the reduction is even greater.

Studying Fennoscandian Uplift by GRACE

Gabriel Strykowski et al.
Danish National Space Center, Denmark

In our presentation we will discuss the merits of a new space-domain technique based on the power series expansion of the reciprocal distance function which addresses the above disadvantages of the existing space-domain techniques. The gravitational attraction of the known source can be pre-computed and stored as coefficients (of the power series expansion of the field) in few support field points. Subsequently, this information can be used to reconstruct (any) field component of the gravitational attraction of a known source in a 3D-domain around the support point. One should emphasize, that the method is not merely an interpolation between the support points. The details of the field approximation (to a pre-defined degree of accuracy) in the 3-D domain are preserved. Furthermore, the method can accommodate complex (i.e. geophysically realistic mass density models within the topography) and the mass density integration must be done only once and subsequently stored as coefficients.

One application that we have in mind while developing the method concerns the practicalities of studying the land uplift in Fennoscandia by GRACE. The (GRACE) satellites fly along an orbit which is not the same every time the GRACE satellites fly over the study area. Using the technique described above the gravitational response of the topography can be approximated along-orbit to a controlled degree of accuracy. If the land is uplifted, the whole topography moves up (possibly at different rates in different places). Thus, an indication of land uplift is not merely a dubious bias/tilt of the gravitational signal in time, but can be studied in details.

Re-advance of the Qassimiut Lobe

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[1]Danish National Space Center, Denmark

Here we discuss the Ice sheet evolution in southern Greenland (south of 62 deg N) and especially the segments of the ice sheet, Qassimiut lobe, which experienced notably large changes in the dimensions during the Holocene.

The inland Ice margin in south Greenland lies mainly in high altitude areas at about > 900 m descending to low levels at narrow outlet glaciers. The about 100 km wide Qassimiut lobe has ts margin below altitude of 500 m and is situated on a relative lowland area. East to the Qassimiut lobe we have the highland area and the Julianehåb Ice Cap, which is situated along the Alpine Mountains. To obtain an estimate of the retreat behind the present ice sheet margin, we compare our observed secular uplift rate at Qaqortoq (using GPS) with 6 different models of an advancing Qassimiut lobe.

OCTAS: Ocean Circulation and Heat Transport between the North Atlantic and Arctic Sea

Solheim, D. [1], **Drange, H.**, **Gidskehaug, A.**, **Johannessen, J.**, **Nahavandchi, H.** [2], **Omang, O.C.D.** [1], **Pettersen, B.R.**, **Plag, H.-P.**

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The Norwegian OCTAS Project, running from 2003 to the end of June 2007, focuses on the ocean circulation in the Fram Strait and adjacent sea with the main objective to improve sea surface topography determination and to study the impact on ocen modelling. The overall aim of this proposal is to enhance Norwegian capacity in Earth observation (EO) technologies in a coordinated way by promoting and developing methods for the joint exploitation of current missions like CHAMP, GRACE, and JASON and the approved European Space Agency ENVISAT (Radar Altimeter) and GOCE missions for ocean circulation studies and associated climate modelling and operational data assimilation.

A central quantity for studying and understanding the ocean circulation is the mean dynamic topography (MDT), which is the difference between the mean sea surface (MSS) and the geoid. The MDT provides the absolute reference surface for the ocean circulation and is, in particular, expected to improve the determination of the mean ocean circulation. This, in turn, will advance the understanding of the role of the ocean mass and heat transport in climate change.

Ocean Circulation and Transport between the North Atlantic and Arctic Sea -- status report 2006

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The OCTAS project is a multidisciplinary approach to determine the mean dynamic sea surface topography (MDT) in the Fram Strait and adjacent seas. This will serve as input to ocean circulation and transport studies in the polar region. Improved determination of MDT will allow assessment of its impact on circulation studies and associated climate modelling. We report results of efforts to obtain new air-borne gravity data supported by GPS and subsequent derivation of a regional high accuracy gravimetric geoid. Mean sea surfaces from satellite altimetry and mean dynamic topography from climatology and hydrography are under development. A preliminary assessment of these data sets have been made and techniques are being developed to optimally estimate quantities in an integrated approach.

Preparing for EGM06 – The DNSC06 high-resolution global marine gravity

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The latest version (DNSC06) of the formerly KMS global marine gravity fields is presented, This gravity field has a resolution of 1 minute by 1 minute and covers all marine regions of the world including the Arctic Ocean up to the North Pole. By starting out from the original waveform data and retracking the entire ERS-1 GM mission using a highly advanced expert based system of multiple retrackers the return time from both the open sea surface and from all ice-covered regions within the coverage of the ERS-1 can be derived with higher accuracy that presently available.

This presentation describes the combined effort in improving the altimetric data sets in coastal and near coastal regions. Expert system tracking and regression to 2 Hz (3 km) and its effect on gravity field modelling close to the coast are presented and extensive comparisons carried out at the National Geospatial-Intelligence Agency is also presented.

Large scale hydrology and changes in gravity from GRACE

Ole Andersen

DNSC. Juliane Maries Vej 30, DK-2100 Copenhagen Ø.

One of the most poorly observed components of the climate system is continental-scale water storage and its variations on annual to interannual scales. Indeed, available ground observations are generally of very small spatial or temporal scope and models driven with observed forcing seldom agree on simulated terrestrial water storage. The recently launched twin satellite mission GRACE has the capability of detecting mean seasonal variations of terrestrial water storage for large river basins.

We demonstrate here the skill of GRACE data in detecting interannual variability in terrestrial water storage by jointly analysizing observations from GRACE, gravity field variations from in situ observations by the GGP stations in Europe, and observations from a hydrological model GLDAS).

In this study we will also investigate the possibility of applying available remote sensing data from GRACE and satellite altimetry as a supplement to existing hydrological studies. The GRACE gravity changes are analysed using a local MASCON approach derived by NASA/GSFC, solving for mass change at 10-day intervals using 4 deg X 4 deg blocks from GRACE level 1B data. ENVISAT altimetry over the region have been submitted to the EARRS Expert-retracker System in order to derive height of rivers, in particular the Ganges and Brahmaputra rivers. The EAPRS system has the ability to recovers nearly unterinerrupted time series over these rivers. GRACE derived mass change from 2002 to 2004 have been studied along with altimetry for the same period.

An Offshore height reference surface Altimetric Mean Sea Surfaces (DNSC06-MSS)

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The DNSC 06 Mean Sea Surface (MSS) is the physically observed time-averaged height of the ocean's surface derived from a total of 6 different satellites and a total of 8 different satellite missions like the T/P, T/P Tandem Mission, Jason-1, ERS1 ERM+GM, ERS2 ERM, GEOSAT GM, and GFO-ERM data. For all mission the MSS have been derived with what is believed to be the best available geophysical and range corrections.

We present the new Altimetric Mean sea surface called DNSC-06 MSS which has been derived from satellite altimetry over the most recent 12 years of satellite altimetry and is the closest proxy of the mean sea surface that can be derived.

Evaluation of the available mean sea surfaces will be carried out in GOCINA study region in the Northern Atlantic region and in the Baltic Sea. An extended comparison will also be presented in the Arctic Ocean to demonstrate the impact of improved geoid and mean sea surface modeling to derived reliable synthetic Mean Dynamic topography.

Improvement in Global and local tide modelling (Linear and non-linear tides on the Northwest European shelf).

Ole Andersen[1], **R. Ray**[2], **Lana Erofeeva**[3], and **Gary Egbert**[3]

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Accurate sea level measurements from the TOPEX/POSEIDON satellite have vastly improved our knowledge about global ocean tide since its launch in 1992. One of the outstanding problems in global tidal modelling is accuracy in shallow water regions, where complex tidal pattern, and non-linear tides degrade the global model. This calls for high resolution tidal modelling and inclusion of non-linear shallow water constituents. These constituents cause a considerable part of the tidal variability on the shelves. On the northwest European shelf the tides are dominated by semi-diurnal constituents and their shallow water constituents (M4, MS4, MNS2, MN4, and M6). One example is the M4 constituent, which exceeds 30 cm in the English Channel. New tidal models for the non-linear tides have been derived using coastal tide inversion, assimilating multi-mission altimetric observations into high resolution hydrodynamic models. Shallow water tides have shorter spatial wavelength, and the importance of high quality bathymetry and altimetry from both the T/P and the recent interlaced T/P Tandem Mission will be demonstrated

Session: Structure of the work in NKG during the time period 2006-2010

Sessionchairman: Björn Engen
Secretary: Bo Jonsson

The Presidium of NKG decided at the meeting in Gävle on 16-17 March 2006 to develop a proposal for the structure of the work in NKG during the next four years period to be presented at the NKG General Meeting. In collaboration with the NKG Working Groups a proposal was developed during the spring 2006 and presented for the participants of the NKG General Meeting on Monday 29 May and reviewed by the meeting on Wednesday 31 May. After some changes agreed in the review, the meeting approved on Friday 2 June the structure of the work in NKG during the time period 2006-2010 shown below.

General

- The Work in NKG should be carried out like today in Working Groups, Task Forces and Projects.
- The number of Working Groups, decided every fourth year by the General Assembly, should be like today 4-6.
- Task forces and projects should be limited in time and nominated by the NKG Presidium.
- An improved coordination of the times for the meetings of the Working Groups and the Presidium is desirable.
- It is the ambition to improve the interaction between the Presidium and the Working Groups by inclusion of the Working Group chairmen in the Presidium; this implies a modification of the regulations for NKG
- Appointed Working Group chairmen and members of the Presidium shall be financially supported by their organisations for participation in meetings and other relevant NKG activities
- The tasks for the Working Groups should be defined by the General Assembly.
- NKG and NKG Working Groups shall interact with international bodies such as EUREF and IAG concerning issues, which are related to the Global reference system and other relevant NKG activities**.**

Working Group for Geodynamics

Key words: gravity change, crustal motion

Objectives: Geodynamics studies of the deformation of the solid Earth and changes of the gravity field with emphasis on the earth's crust. Surface based measurements are used to derive geodetic and geophysical parameters of the earth interior. Phenomena are studied with the aim to understand their causes and consequences, and the mechanisms involved. The phenomena include: Land uplift and glacial isostatic adjustment, plate tectonics, earth tides and loading effects due to variations in the ocean, the atmosphere, and the hydrosphere, local tectonic and man-made deformations.

Activities:

- The phenomena are studied with a wide range of techniques, comprising classical positional geodesy, precise levelling, satellite positioning, absolute gravimetry, precise recording gravimetry, monitoring of the sea level, and satellite altimetry.
- Coordination of investigations of gravity change, in particular absolute gravity campaigns and measurements on the gravity lines.
- Local studies of the temporal gravity field and associated perturbing parameters (oceanic, hydrological, meteorological effects, crustal loading, etc.)

Working Group for Geoid Determination

Key words: Geoid, figure of the Earth, gravimetry, satellite gravimetry

Objectives: The aim of the working group is to compute a 1-cm geoid model for the Nordic land and marine areas by combining satellite and terrestrial gravimetric data as well as GPS derived geoidal undulations

Activities:

- Make an effort to ensure that all Working Group Members have sufficient access to relevant data
- Study the error propagation of the current theory and gravimetric data for NKG geoid modelling.
- Investigate the theory and methods being used, identify possible refinements and/or improvements and implement these.
- Collect and validate gravity data, both new and existing data
- Contribute to GOCE and other satellite gravimetric missions and make use of such data.
- Compute a gravimetric geoid and compare this model with geoid heights determined by GPS/levelling.
- Carry out an optimum combination of the gravimetric geoid and geoid heights determined by GPS/levelling for the purpose of new height surface definition,
- Compute a marine geoid for an optimal use of satellite altimetry in oceanography.

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Working Group for Height Determination

Keywords: Height determination methods, height systems, vertical datum

Objectives: Adjustment of the Nordic Height Block in a joint Nordic height system, support for the definition, computation, implementation and maintenance on the new height systems and studies of methods for height determination.

Activities:

- The analysis of the adjustment of the levelling nets around the Baltic Sea is not yet completed.
- The national levelling of Norway, Iceland and the Baltic Countries are still going on.
- The technical development of the present height determination methods (precise levelling, trigonometric levelling), quit new methods and those applying the sea level and GPS/Geoid, belong all to the scope of activities by the Working Group.
- The study of the Nordic land uplift models will continue. New data from the area of Baltic Levelling Ring will be incorporated in co-operation with the countries involved
- The connection of the Nordic levelling Block to the European and the World height systems belongs also to the scope of activities by the Working Group.
- The test field measurements, the error analyses and the study of the digital levelling technique will be the main issues by the Working Group.

Working Group for Positioning and Reference Frames

Keywords: Positioning, four-dimensional reference frames

Objectives: Studies of methods for positioning using satellite techniques, development of methods for the monitoring of reference frames and implementation of the results from the monitoring in the realisation of the reference frames for practical use. The Working Group shall also be a forum for exchange of information and studies related to the four-dimensional reference frames and the present reference frame issues.

Activities:

- Recommendations for the implementation of ITRF 2005
- Studies of methods for high precision three dimensional positioning using satellite observations, being a forum for data and information exchange on high precision positioning
- Studies of methods for the monitoring of reference systems, networks of permanent reference stations and repeated campaigns
- Exchange of information and studies related to the present reference frame issues, e.g. methods for transformation between different reference frames, selection of reference frames, kinematic height systems
- Studies of the concept for four dimensional reference systems issues
- Act as NKG regional GNSS Data Analysis Centre for EUREF/IGS

Task Force “NGOS (A Nordic Geodetic Observing System)”

Based on the review of the proposal of the NKG structure on 31 May the Presidium decided on their meeting in the evening of 31 May that the Task Force NGOS continues during the next four years period.

Key words: Based on the review of the proposal of the NKG structure on 31 May the Presidium decided on their meeting in the evening of 31 May that the Task Force NGOS continues during the next four years period.

Objectives: Coordination of the design of a Nordic Geodetic Observing System (NGOS) and the Nordic contribution to the development of an European Combined Geodetic Network” (ECGN) and a Global Geodetic Observing System (GGOS)

Activities:

- Altimetry, InSar and other relevant remote sensing technologies
- VLBI, GNSS, SLR, DORIS-
- Satellite Orbits, Gradiometers, Absolute Gravimeters, Recording Gravimeters
- Access and distribution of data, taking into consideration different restrictions
- Possible transition of the existing observations, observation sites and techniques to new ones
- Contribution to the maintenance of reference systems

Task Force for the coordination of the Nordic VLBI-activities

Key words: Geodetic VLBI, baseline length measurements, contribution to GIA (Glacial Isostatic Adjustment) research and NGOS (Nordic Geodetic Observing System).

Objectives: Strengthen the knowledge and efficiency in the operation of large and complex infrastructure under harsh conditions. The Task Force shall also prepare and produce data in a Nordic VLBI- network as an independent, additional input to the Working Group for Positioning and Reference Frames.

Activities:

- Exchange VLBI experience between the Nordic VLBI stations.
- Aim at compatibility with the future VLBI2010 recommendations.
- Establish contacts to (so-far) non-geodetic VLBI stations in the peripheral bulge and investigate possible cooperation.
- Investigate the possibility of an increased number of Nordic VLBI observing sessions.

- Investigate possible VLBI phase delay solutions.
- Aim at use of eVLBI data transfer.
- Study the use of software correlation.

The Project Nordic Positioning Service

Objectives: On directions from the Directors General of the Nordic Mapping authorities coordinate and develop the infrastructure of the Nordic Permanent reference stations.

Activities:

- Connections of the control centres of the national networks of permanent reference stations to each other for real-time data exchange via leased lines
- Development of services and applications based on the basic Nordic infrastructure of permanent reference stations
- Contribute to the on-going standardisation work related to issues of the establishment and use of networks of permanent reference stations

Project design: The project is organised in a Steering Committee and a Project group. The Steering Committee is appointed by the Presidium.

Session: Resolutions

Chairman: Niels Andersen
Secretary: Bo Jonsson

To the Resolution Committee at the 15th General Meeting, Copenhagen, Denmark 2006, the following members were appointed:

Niels Andersen, Denmark, chairman
Markku Poutanen, Finland
Oddgeir Kristiansen, Norway
Bo Jonsson, Sweden

Niels Andersen read all the resolutions and then one by one the resolutions were discussed by the NKG General Assembly. The accepted resolutions follow below.

Resolutions adopted at the 15th General Meeting of the Nordic Geodetic Commission in Copenhagen 29 May – 2 June 2006

No. 1 Copenhagen 2006-06-02

The Nordic Geodetic Commission

recognizing that the subsiding peripheral bulge contains important information about the postglacial rebound process,

noting that groups outside the NKG community are carrying out observations and studies that are useful for the understanding of the postglacial rebound process,

noting the usefulness of combining techniques, results and expertise with measurements and studies from a wider area,

noting the need of a unified vertical datum for the entire region,

recommends the Working Groups to cooperate with research groups on an international level with the specific aim to better understand the entire rebound process and changes of position, height and gravity not only in the uplift area, but also in the peripheral area.

No. 2 Copenhagen 2006-06-02

The Nordic Geodetic Commission

recognizing that the number of permanent stations for GNSS is increasing rapidly in the Nordic area,

noting that there is a lot to gain by coordinating the establishment of permanent reference stations in the border areas between the Nordic countries,

noting the benefits of exchange between the Nordic countries of data from permanent GNSS-stations and knowledge and experiences in the field of establishment, operation and use of permanent reference stations,

recommends the Project Nordic Positioning Service to continue their efforts to coordinate the Nordic networks of permanent reference stations and to establish Nordic Positioning Services.

No. 3 Copenhagen 2006-06-02

The Nordic Geodetic Commission

recognizing that the Nordic countries have implemented national realizations of ETRS 89,

noting that ETRS89 has been proposed for common use within the EU,

noting that the national realizations have already been introduced to the users and cannot be changed,

noting that models for intraplate deformation are now available and that such models have not been applied in the official national realizations of ETRS89.

noting that positioning services at the sub dm-level without apparent ground control have been proposed (e.g. from Galileo),

recommends that appropriate national representatives in their connections to the EUREF community work for a clarification regarding a handling of intraplate deformations in future realizations of reference systems and transformations to ETRS89.

No. 4 Copenhagen 2006-06-02

The Nordic Geodetic Commission

recognizing the current development of Global Observing Systems, particularly the Global Geodetic Observing System (GGOS) and the ultimate importance of such development for the future of geodesy, geodetic networks and stable infrastructure for global monitoring,

noting the membership of GGOS in International Global Observing System – Partnership (IGOS-P) and Group on Earth Observations (GEO),

noting the challenges in long-term monitoring and maintaining geodetic infrastructure (e. g. ensuring networks and local ties) and expertise due to economical and political reasons,

recommends that National Authorities and geodetic institutions support the development of GGOS, including its incorporation in IGOS-P and GEO, and support the development of the Nordic Geodetic Observing System (NGOS) as a regional implementation of GGOS.

No. 5 Copenhagen 2006-06-02

The Nordic Geodetic Commission

recognizing the importance of high precision geoid models for practical engineering purposes and optimal use of satellite altimetry in monitoring ocean circulation and sea ice thickness determination,

noting that such a geoid model will provide the opportunity to adopt a unified height system for the Nordic countries and the surrounding marine areas to serve the GNSS and oceanographic users,

noting the importance of verifying the improvements in geoid model computation,

recommends that efforts are made on national level to make gravity and digital elevation data available for the NKG Working Group for Geoid Determination, and that high precision GNSS and levelling data are provided for the verification and assessment of the computed geoid models.

No. 6 Copenhagen 2006-06-02

The Nordic Geodetic Commission

recognizing the need for freely available and homogeneous time series and improved modelling for geophysical research from all geodetic techniques,

noting the importance that the Nordic countries increase their competence and knowledge in analyzing data from all the primary space geodetic techniques,

noting the need for a re-computation of GNSS orbits, clocks and Earth Orientation Parameters (EOP's) in a well defined, long term stable reference frame,

noting the need to study various reference frame realizations including a combination of space geodetic data both on the covariance level and on the observation level,

recommends the processing of a consistent set of time series from all the available geodetic techniques in a unified defined reference system and in a long term stable reference frame,

in particular

- all permanent GNSS and VLBI stations in the Nordic countries,
- all super conducting gravity data in the Nordic countries.

No. 7 Copenhagen 2006-06-02

The Nordic Geodetic Commission

recognizing the need for qualified geodetic expertise in the future,

noting a general decrease in number of students in natural sciences,

recommends the Geodetic institutions to work for making young people interested in natural science, especially in the field of Geodesy.

No. 8 Copenhagen 2006-06-02.

The Nordic Geodetic Commission and its members

present at the 15th general meeting of the Commission in Copenhagen express their sincere thanks to Danish National Space Center, to National Survey and Cadastre Denmark, to the scientific committee and to the local organizing committee for the excellent arrangement and warm atmosphere during the meeting and at the social events.

Session: Confirmation and Elections

Session chairman: Björn Engen
Secretary: Bo Jonsson

Confirmation of the Vision for NKG

A Vision for NKG had been developed by the Presidium and was presented for the participants of the NKG General Meeting on Monday 29 May and reviewed by the meeting on Wednesday 31 May. After some changes agreed in the review, the meeting approved on Friday 2 June the Vision for NKG shown on the next page.

Confirmation of the changes of the regulations for NKG

With reference to the approved structure of the work of NKG during the next four years period the meeting agreed to modify § 4 in the regulations for NKG shown below.

§ 4

Kommissionens angelägenheter handhas av en styrelse, bestående av högst två representanter från varje landsgrupp, samt ordförandena för de särskilda sektionerna, se § 7 nedan

Styrelsen utgör kommissionens permanenta organ och samlas i regel till möte varje år. Styrelsen utgör kommissionens kontaktorgan mellan nordiska geodeter, mellan nordiska geodetiska institutioner och till nordiska myndigheter. Styrelsen kan utforma och samordna nordiska projekt.

I beslut som fattas av styrelsen genom votering har varje nation en röst.

The full version of the regulations for NKG can be found two pages ahead in these proceedings.

Establishment and confirmation of NKG Working Groups

With reference to the approved structure of the work of NKG during the next four years period the meeting agreed to

- carry on with the four Working Groups Geodynamics, Geoid determination, Height Determination and Positioning and Reference Frames
- carry on with the Task Force NGOS and to establish a new Task Force for the coordination of the Nordic VLBI-activities

The following chairpersons for the Working Groups were elected:

Geodynamics:	Martin Lidberg, Sweden
Geoid Determination:	Dag Solheim, Norway
Height Determination:	Olav Vestøl, Norway
Positioning and Reference Frame:	Per Knudsen, Denmark

Appointment of Members to the NKG Presidium

As national representatives in the new Presidium the following persons were announced*:

Denmark:	Niels Andersen, Lolita Bahl
Finland:	Risto Kuittinen, Markku Poutanen
Norway:	Björn Engen
Sweden:	Bo Jonsson, Anders Olsson
Iceland	Thorarinn Sigurdsson

The Presidium elected Anders Olsson as chairman and Bo Jonsson as secretary for the next four years period.

*Note the Working Group chairmen are also members of the Presidium

VISION FOR NKG

The Nordic Geodetic Commission shall improve national capabilities by:

- ✓ promoting cooperation in geodetic tasks, education and research

- ✓ promoting optimal use of resources and data
  - across borders
  - in joint observations – and research projects
  - in common use of all equipment available as well as data, computing and analysis capabilities

- ✓ promoting unified Nordic solutions (as part of a global densification) for
  - ITRF solutions and EUREF transformations
  - height reference
  - land uplift
  - geoid
  - real-time services
  - standards
  - and as required

- ✓ proposing joint Nordic representation in international forums

- ✓ strengthening the network of competence

In order to achieve the above, importance success criteria will be*:*

- ✓ to focus and exploit the most advanced knowledge and relevant available resources in each country

- ✓ to concentrate the main activities to priority areas of common Nordic interest

- ✓ to treat other activities as information

- ✓ to inform users, politicians and other authorities about NKG and its activities

STADGAR FÖR NORDISKA KOMMISSIONEN FÖR GEODESI

Revidering fastställd vid allmänt nordiskt geodetmöte i Köpenhamn den 2 juni 2006.

§ 1

Nordiska kommissionen för Geodesi (NKG) är en sammanslutning av geodeter i Danmark, Finland, Island, Norge och Sverige, vars ändamål är att främja nordiskt geodetiskt samarbete, utbildning och forskning.

§ 2

Till medlem av kommissionen kan envar inväljas, som antingen genom utbildning eller genom ämbetsställning har anknytning till geodetisk verksamhet.

Kommissionens medlemmar indelas i fem landsgrupper. Frågor om medlemskap i kommissionen avgörs inom varje landsgrupp, I övrigt står det landsgrupperna fritt att organisera sig efter eget gottfinnande.

§ 3

Kommissionen samlas i regel vart fjärde år till allmänt nordiskt geodetmöte. Mötet är kommissionens högsta beslutande organ. Där icke särskilda skäl annat påkallar, skall uppdraget att arrangera mötet växla i tur mellan landsgrupperna.

§ 4

Kommissionens angelägenheter handas av en styrelse, bestående av högst två representanter från varje landsgrupp, samt ordförandena för de särskilda sektionerna, se § 7 nedan.

Styrelsen utgör kommissionens permanenta organ och samlas i regel till möte varje år. Styrelsen utgör kommissionens kontaktorgan mellan nordiska geodeter, mellan nordiska geodetiska institutioner och till nordiska myndigheter. Styrelsen kan utforma och samordna nordiska projekt.

I beslut som fattas av styrelsen genom votering har varje nation en röst.

§ 5

Kandidater till styrelsen utses av respektive landsgrupp. Styrelsen fastställs av allmänt möte. Styrelsen utser inom sig ordförande och sekreterare. Ordföranden tecknar på styrelsens vägnar kommissionen i alla officiella sammanhang. Valet till styrelsen gäller en period fram till nästa allmänna möte. Omval kan ske. Dock kan ordföranden fungera som sådan i högst två på varandra följande perioder.

§ 6

Allmänt möte förbereds och genomförs av en organisationskommitté, som väljs av och inom landsgruppen i det land, där mötet är avsett att hållas.

Första cirkulär om mötestidpunkt utsänds minst nio månader före mötet. Dagordningen för mötet uppgörs av organisationskommittén efter samråd med styrelsen och tillställs samtliga medlemmar minst tre månader före mötets början.

Över mötets förhandlingar och beslut skall organisationskommittén låta avfatta referatprotokoll, som delges alla medlemmar.

§ 7

För att främja det löpande samarbetet inom visst geodetiskt ämnesområde kan kommissionen bilda särskild sektion, för en period fram till nästa allmänna möte.

Kommissionen väljer sektionens ordförande.

Sektionen samlas efter behov i perioden mellan allmänna möten och skall tillställa kommissionens styrelse kopia av mötesprotokoll, samt rapportera till allmänt möte.

Sektionen kan förnyas vid allmänt möte.

§ 8

Kommissionen uppbär inga medlemsavgiften. Allmänna kostnader i samband med anordnande av möten, utskrivning och distribution av protokoll m m skall bestridas av den landsgrupp, som står som mötets organisatör.

§ 9

Kommissionens handlingar bevaras genom styrelsens försorg. Av stadgar, mötesbeslut och andra viktiga handlingar skall ett exemplar finnas i varje landsgrupps arkiv.

§ 10

Beslut om ändring eller tillägg i dessa stadgar fattas genom enkel majoritet vid allmänt möte. Sådant förslag skall avfattas skriftligt och tillställas styrelsen före i januari det år mötet skall avhållas.

§ 11

Beslut om kommissionens upplösning skall fattas vid allmänt möte. Förslag om upplösning av kommissionen skall undergå samma procedur som förslag om stadgeändring.

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