# Geodetic Operations in Finland

# 2008 – 2011

Edited by

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## 1.1 The national realization of the ETRS89: EUREF-FIN

The Finnish Geodetic Institute (FGI) and National Land Survey of Finland (NLS) are responsible for creating and maintaining national reference frames in Finland. EUREF-FIN is the national realization of the ETRS89. The first order network (E1), including 12 FinnRef® stations and 100 other benchmarks, was measured 1996–97. It defines the EUREF-FIN reference frame. This network was densified with 350 points by the FGI in 1998–99. This network is classified as the EUREF-FIN network of order Ib (E1b). The National Land Survey of Finland and the Finnish Maritime Administration have densified these networks with a second order network (E2) that was completed in 2008. It consists of approximately 2500 points (Figure I-1).

## 1.2 The national realization of the EVRS: N2000

In order to maintain an accurate nationwide height system, precise levellings must be repeated regularly due to the Fennoscandian land uplift (postglacial rebound, PGR). The Third Levelling of Finland was completed in 2006. The new national height system N2000 was introduced in 2007. It replaces the previous system N60.

The N2000 was realized in Nordic and European cooperation in the framework of the Baltic Levelling Ring (BLR2000). The work with the BLR2000 was coordinated by the Nordic Geodetic Commission (NKG) and supported by the IAG Reference Frame Sub-Commission for Europe (EUREF) and the countries around the Baltic. The datum of the N2000 derives from the NAP (Normaal Amsterdams Peil) through the adjustment of the BLR2000. As in the BLR2000, the land uplift model NKG2005LU was used to reduce all the observations to the epoch 2000.0. The N2000 complies with the definitions (2007) of the European Vertical Reference System (EVRS). The NKG2005LU and the epoch 2000.0 were subsequently adopted by EUREF for the North European part of the most recent pan-European realization of the EVRS, the EVRF2007. Consequently, the differences between the N2000 and the EVRF2007 are small, less than one centimetre.

Metric heights in the N2000 are up to 0.4 m larger than the metric heights in the N60 (Fig. I-2). This is primarily caused by the land uplift: the reference epochs are 2000.0 and 1960.0, respectively. The difference in the datums (NAP vs. mean sea level in Helsinki), the difference in tidal systems (zero-free vs. mean-tide) and the difference in the conversion from geopotential numbers to metric heights (normal heights vs. orthometric) also contribute to the difference between the N2000 and the N60 heights, in this order of importance.

The monument of the Third Levelling of Finland was erected above the fundamental benchmark PP2000 at the Metsähovi Geodetic Observatory in 2007 (Figure I-3).

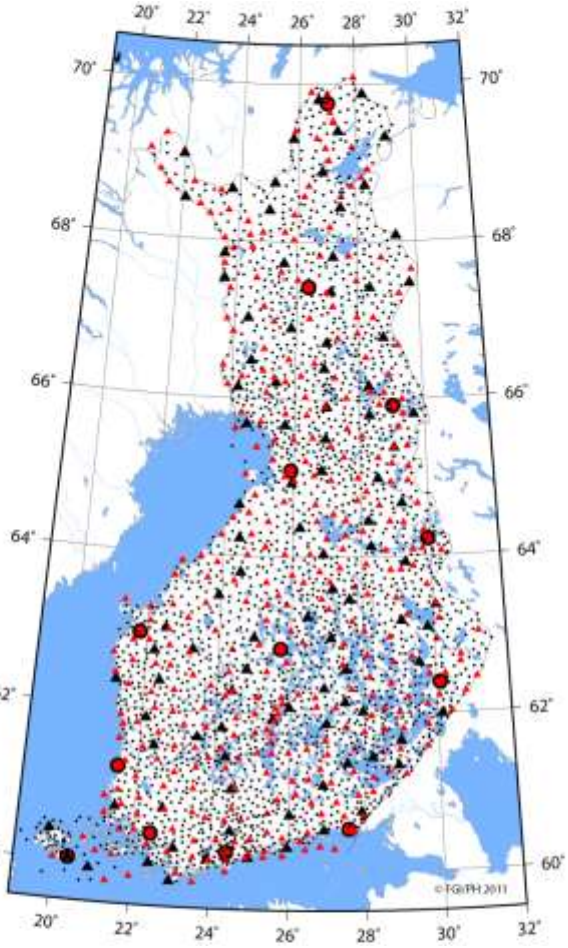


**Figure I-1.** EUREF densifications in Finland. FinnRef® permanent GPS stations (large red circles) and the densification of 1996–97 (black triangles) constitute the First order EUREF network in Finland and define EUREF-FIN, the national realization of ETRS89. Small red triangles show the order Ib network measured in 1998–99. Black dots denote the Second order densification.

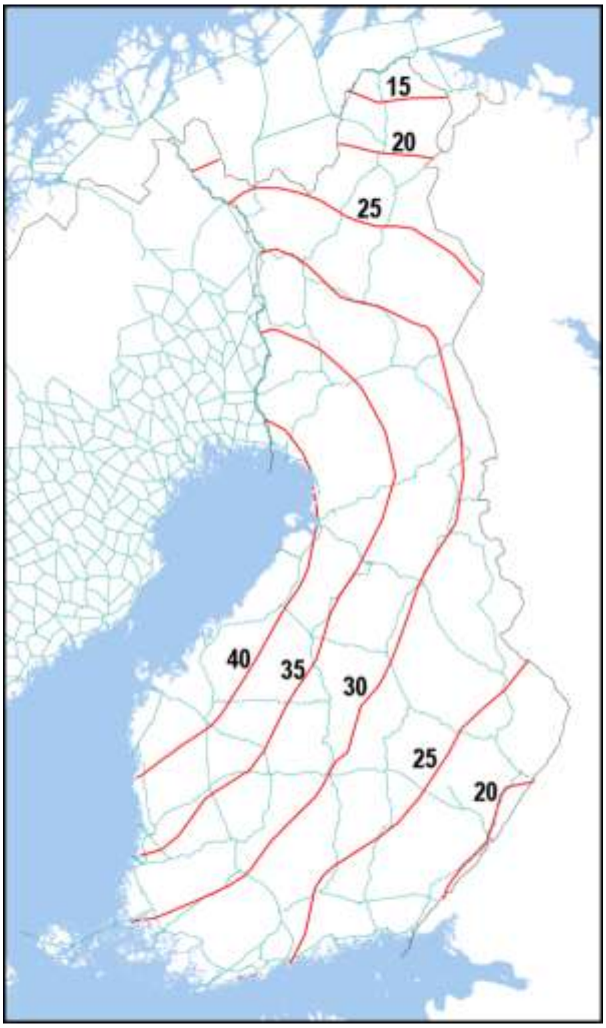


**Figure I-2.** Difference (in centimetres) between metric heights expressed in the N2000 system and metric heights expressed in the N60 system, for stable bench marks in the precise levelling network.

**Figure I-3.** The monument of the Third Levelling of Finland. The fundamental benchmark is in bedrock under the monument, not visible. (Photo: Markku Poutanen)

## 1.3 Implementation of EUREF-FIN and N2000

In Finland, there is no binding legislation on geodetic systems: in principle, government institutions and municipalities are free to choose the reference frame that they deem to be the most suitable for their use. This has led to a situation where e.g. municipalities have either stayed at one of the old national reference frames or created their own local reference frame that is loosely connected to one of the nationwide reference frames. This has led to the need to constantly transform between various old frames and the contemporary frames in which the measurements are made.

In order to harmonize the frames used, the FGI with the National Land Survey have prepared a set of recommendations for public administration that promote the use of the EUREF-FIN and the N2000. Now also the INSPIRE directive of the European Commission requires local authorities to make their geospatial data available in these systems.

EUREF-FIN was introduced a decade ago. Several governmental authorities have already changed to EUREF-FIN, and as an example national topographic maps have been printed in ETRS-TM35FIN (UTM projection of EUREF-FIN) for a couple of years now. However, within local authorities the change has been slower: only recently cities and municipalities started to change over to EUREF-FIN but this is now progressing. The main driving forces seem to be the INSPIRE directive, the increasing data exchange and also the fact that the old reference frames do not fulfil the present requirements anymore.

The N2000 height system was introduced in 2007. The adoption of N2000 is in progress. Government institutions started to apply the N2000 in their work in 2008. Only a few municipalities have changed their system so far. However, it seems that several more will do it already in the near future. One of the incentives is that the PGR complicates the relation of old municipal height systems to the national system. If the epoch difference is large enough, this relation cannot always be described by an offset: even tilt parameters may be needed.

The first step in the implementation of the N2000 was to produce an accurate transformation from the N60 height system to the N2000, covering the country in detail including areas where the heights were derived from lower-order levelling lines. This transformation was realized 2008–2009 by the NLS. It is based on a triangulation network formed by a selection of first and second order levelling benchmarks (Fig. I-4). Such a trianglewise transformation is capable of correcting local distortions caused by e.g. incomplete accounting for the PGR in earlier lower-order levelling.

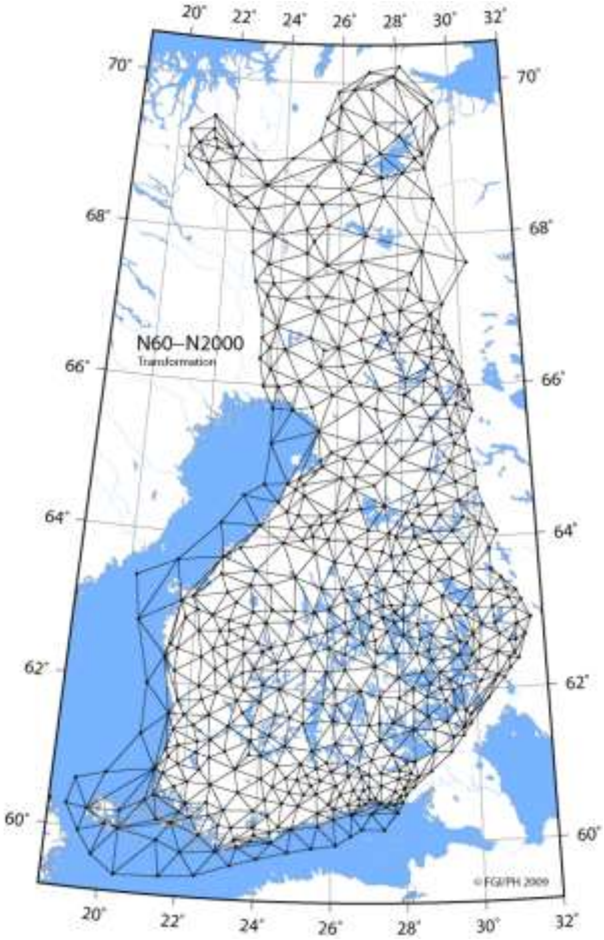


**Figure I-4.** Transformation from the previous nationwide height system N60 to N2000 is based on a triangulated selection of first and second order levelling benchmarks.

## 1.4 The permanent GPS network FinnRef®

The Finnish permanent GPS network FinnRef® consists of 13 stations. The network is maintained by the FGI and it is the basis of the national ETRS89 realization. It is also the link to the international reference frames through one IGS station (Metsähovi) and four EPN stations (Metsähovi, Vaasa, Joensuu, Sodankylä). All data from FinnRef® stations is transferred via broadband Internet connections (ADSL) hourly or in real time. Four FinnRef® EPN stations provide real time data stream to EUREF-IP service.

Time series of FinnRef® network have essential role in geodynamical studies, e.g. for determination of Glacial Isostatic Adjustment (GIA). Since changes in instrumentation, especially change of antennas or radomes have been shown to cause jumps in time series, FinnRef® stations have been kept unchanged since the beginning.

The stations are also monitored independently from GNSS with precision tacheometry and precise levelling. The stability of the antenna platforms is controlled by tacheometer measurements that are repeated every 2–3 years. Recently we have also started to use precise levelling for controlling the height of the GPS antenna with respect to reference benchmarks.

**Figure I-5.** Control measurement of the mast of the permanent GPS station. The stations are monitored independently from GNSS with precision tacheometry and precise levelling. (Photo: Olli Wilkman)

Using a digital precise levelling instrument we put the rod upside down under the antenna, and in normal position on the benchmark (Fig. I-5). This way the collimation error of the level and the zero-point error of the rod do not cancel out in the result, their influnce is doubled. Therefore we have determined the zero-point error of the rods in our rod comparator, and the collimation error is always controlled before measurements. We are able to use levelling at six stations. No significant movements of the monuments have been found in these regularly repeated measurements.

## 1.5 Metsähovi fundamental station

The Metsähovi Geodetic Observatory was founded in 1978 and it has through the years become an essential part of the activities of the FGI. The instrumentation covers the satellite laser ranging (SLR), geodetic VLBI, GPS and GLONASS receivers, DORIS beacon, superconducting gravimeter and seismometer. In addition the national gravity reference station and the fundamental benchmark of N2000 height system are located in Metsähovi. Due to its versatile set of instruments, it can be called a Fundamental Station in the global geodetic network.

As a co-operation project with the Metsähovi Radio Research Station of the Aalto University (formerly Helsinki University of Technology), geodetic VLBI observations started in 2005 were continued during the period 2008–2011. Metsähovi participated in 6–8 geo-VLBI campaigns annually, as a part of the IVS (International VLBI Service) network (IVS-T2) and the European geodynamics project (EUROPE campaigns). These campaigns are carried out for terrestrial reference frame definition. During years 2008–2011 a total of 28 geodetic VLBI sessions were made. Metsähovi participated also in a world-wide VLBI campaign in November 2009 as a special event of the International Year of Astronomy.

The observation data have been transferred to the Bonn correlation centre. The IVS Data Centres, located in Germany, France and USA store the correlated data.

The old Metsähovi Satellite Laser Ranging (SLR) system was discontinued in 2006. A decision was made to purchase a modern kilohertz laser and a contract was signed with the High Q Laser Production GmbH of Austria. The laser ordered is a diode-pumped Nd:VAN solid state laser with a pulse rate up to 2 kHz and the pulse energy > 0.5 mJ. The laser is of the same type that e.g. the Graz and Herstmonceux stations are currently using.

At the same time, a major renovation of the 1 m Cassegrain-Mangin telescope was needed. It includes the replacement of the drive and control system as well as separation of outgoing and incoming signals. A new encoder has been installed to the azimuth ring and, together with new motors, testing will start in summer 2011. The new optical solution for separating outgoing and incoming beam has been developed together with the University of Latvia in Riga and installing of the new system will start in summer 2011.

Parallel to that, work on new 2 kHz operational software is ongoing. It is tailored to our new equipment and is currently capable of dealing with 2 kHz observations frequency. Improvement in the filtering of residuals, automation in the range gate setting, time bias estimation and management as well as smart session planning is implemented. Laser control as well as telescope communication and steering are under development.

The Metsähovi GPS station (METS) continued as a part of the Finnish permanent GPS network FinnRef®. Data were submitted to the computations of the European Permanent GNSS Network (EPN) as well as to the IGS and JPL networks. Also, data from Javad/Legacy GPS/ GLONASS receiver (METZ) were submitted to the GLONASS data centre of the IAG.

The GPS antenna of METS (AOAD/M_B), that had been kept untouched since 1992, was broken down during the summer 2010. The antenna on top of the 20 m high steel grid mast is stabilized with a special invar wire construction which eliminates the thermal expansion of the mast. The broken antenna was replaced with an individually calibrated AOAD/M_T antenna that was directed to true North. To ensure the exact re-location of the new antenna to the stabilization system we measured the tie between antenna and the ground markers with tacheometer before and after the change.

In order to get more precise height difference between the antenna ARP and the ground markers we applied the space intersection technique with a pair of TC2003 tacheometers, prisms and a calibrated carbon fibre measurement rod. From the measurements, the standard deviation of the height differences between the target points on the bottom of the GPS antenna and the ground markers was 0.4 mm. The measurements were repeated after the antenna change, and the height difference between the old and the new ARP were calculated. The aim of the measurements was to verify that the invar stabilization system remains unchanged during the antenna change. Our results were consistent with the height difference determined from physical antenna elements and thus confirm that the stabilization system was successfully preserved during the antenna change.

**Figure I-6.** The antenna on top of the 20 m high steel grid mast is stabilized with a special invar wire construction which eliminates the thermal expansion of the mast**.** (Photo: Hannu Koivula)

**Figure I-7.** VLBI telescope inside the radome. (Photo: Markku Poutanen)

**Figure I-8.** Metsähovi fundamental station. (Background photo: Jyri Näränen)

**Table I-1.** The local tie vectors and their lengths between METS GPS and VLBI reference point and the axis offsets in the static GPS campaign, four kinematic GPS campaigns and tachymetric measurements. The standard deviations (std) of the vector components and axis offsets are included

| campaign | north (m) | std (mm) | east (m) | std (mm) | up (m) | std (mm) | length (m) | axis offset (mm) | std (mm) |
|---|---|---|---|---|---|---|---|---|---|
| static 2h | 37.6121 | 0.4 | -122.3997 | 0.5 | -14.6738 | 0.7 | 128.8863 | -5.3 | 1.0 |
| IVS-T2059 | 37.6086 | 0.2 | -122.4009 | 0.2 | -14.6781 | 0.4 | 128.8869 | -4.5 | 0.6 |
| EUROPE-97 | 37.6080 | 0.3 | -122.4006 | 0.2 | -14.6780 | 0.5 | 128.8864 | -5.0 | 0.7 |
| EUROPE-98 | 37.6071 | 0.3 | -122.4019 | 0.2 | -14.6776 | 0.6 | 128.8874 | -5.2 | 0.9 |
| IVS-T2061 | 37.6094 | 0.3 | -122.3995 | 0.3 | -14.6786 | 0.8 | 128.8859 | 2.0 | 1.1 |
| tachymetric | 37.6105 | 0.1 | -122.4015 | 0.1 | -14.6722 | 0.2 | 128.8874 | 0.3 | 0.2 |
| Combined | 37.6095 | 0.1 | -122.4006 | 0.1 | -14.6751 | 0.2 | 128.8865 | -2.1 | 0.3 |

## 1.6 Local tie between VLBI and GPS at Metsähovi

The local ties between the co-located instruments in Metsähovi have been measured with tacheometers in 1997 and 2004. However, the radome over the radio telescope (Fig. I-7) blocks the visibility to the telescope and makes the precise definition of the geometric centre of radio telescope challenging.

The work on improved local ties, especially for VLBI, was started in 2007. Altogether seven new concrete pillars with a steel antenna platform were built outside the VLBI radome and around the GPS mast. The concrete pillars, fixed tripods and some additional ground points inside the radome form the frame for VLBI local tie measurements. This network was levelled and measured with tacheometer and GPS, and adjusted as a combined network.

The local tie between the IGS station METS and the reference point of the radio telescope antenna was performed with terrestrial and GPS measurements. The reference point of a VLBI antenna is defined as the point to which VLBI observations refer. It is the intersection of the primary axis (azimuth axis) of the telescope with the shortest vector between the primary axis and the secondary axis (the elevation axis). Because there are no physical markers, we have applied an indirect method to determine the reference point.

The first method was to measure positions of targets fixed on the solid structure of the radio telescope with the space intersection technique when the telescope is turned into different positions. This was done using two TC2003 tacheometers. In the second method we carried out static GPS observations with two Ashtech Dorne Margolin type GPS antennas attached to the opposite edges of the radio telescope dish. A total of 110 two-hour sessions in pre-planned VLBI antenna positions were used to determine the VLBI reference point with respect to the GPS station METS.

The methods consume a lot of telescope time. We were able to get nine days for the GPS measurement. Tacheometry observations were taken at times when weather prevented radio astronomical observations.

To overcome the schedule problems, we decided to test kinematic GPS during a geo-VLBI campaign. The first tests were carried out in November 2008. The method along with a new mathematical model developed in 2009 turned out to be promising. The reference point, axis offset and the orientation of the radio telescope antenna were computed. The computation model is suitable for sparse and scattered data as well, not only for data taken in pre-planned circular motion of the antenna.

Comparisons show that the precision achieved with the kinematic GPS method was better than with the static GPS (see Table I-1). This is due to the fact that the static GPS measurements, even over the nine day observation period, give considerably less points than a kinematic GPS solution during a 24-hour geo-VLBI session. The quality of the coordinates of one position of the antenna from static observations was slightly better but not enough to compensate for fewer points. An additional advantage of the kinematic method is that the normal use of the telescope is not interrupted and the tie can be measured simultaneously during a VLBI session.

Our tests show that it is possible to achieve a millimetre level accuracy in local-tie vector determination with the kinematic GPS method. We have used the kinematic GPS method during 14 geo-VLBI campaigns in 2008–2010 and continue using it during the geo-VLBI campaigns.

## 1.7 Transformation from ITRS realizations to national ETRS89 realization

The EUREF created the European Terrestrial Reference System 89 (ETRS89) and fixed it to the Eurasian plate in order to avoid time evolution of the coordinates due to plate motions. However, the Fennoscandian area in Northern Europe is affected by the postglacial rebound causing intraplate deformations with respect to the stable part of the Eurasian tectonic plate.

The Nordic national ETRS89 realizations were created in the 1990s and they have been adopted as the basis for geospatial data. As the most accurate GNSS processing is done in ITRS realizations, accurate transformations to the national ETRS89 realizations are needed. With the official transformation provided by EUREF, residuals reach 10 cm because the transformation cannot describe the effect of PGR.

Only recently has it been possible to construct the first model that also accurately takes into account the horizontal component. The model, created as a Nordic co-operation in the Nordic Geodetic Commission (NKG) and based on more than 10-year continuous time series of GPS observations, greatly improves transformation accuracy compared to the results obtained from global models. Implementing the model for maintenance of the reference frame and for practical surveying, however, still requires further consideration. Already today the deformation of the National EUREF-FIN reference frame is detectable in the most accurate nationwide measurements, but with the new velocity model the validity of the reference frame can be prolonged for many decades.

We evaluated the NKG approach and compared it to the current recommendation given by EUREF with the 100-point first order EUREF-FIN network in Finland. The results show, that by using a high-quality intraplate velocity model, the transformation residuals are reduced to the cm-level (see Fig. I-9 and I-10).

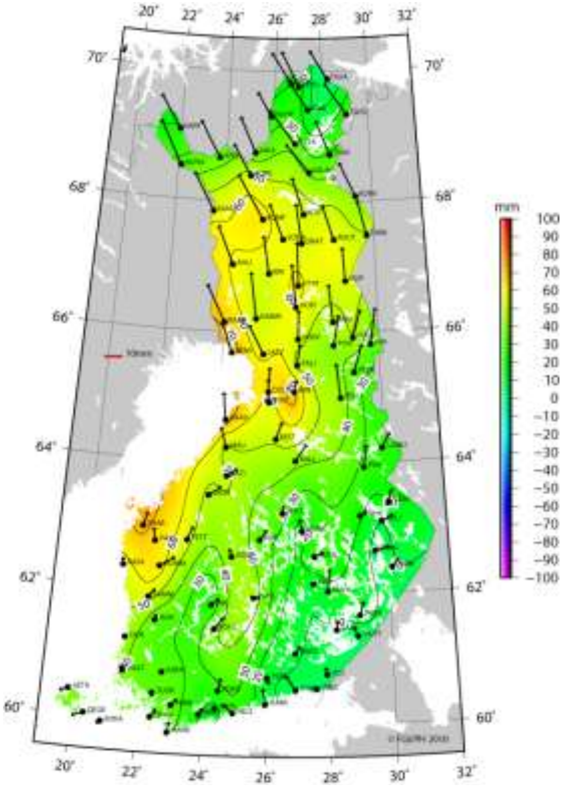


**Figure I-9.** Accuracy of the official transformation provided by EUREF (horizontal residuals shown with vectors and vertical residuals with colour map).

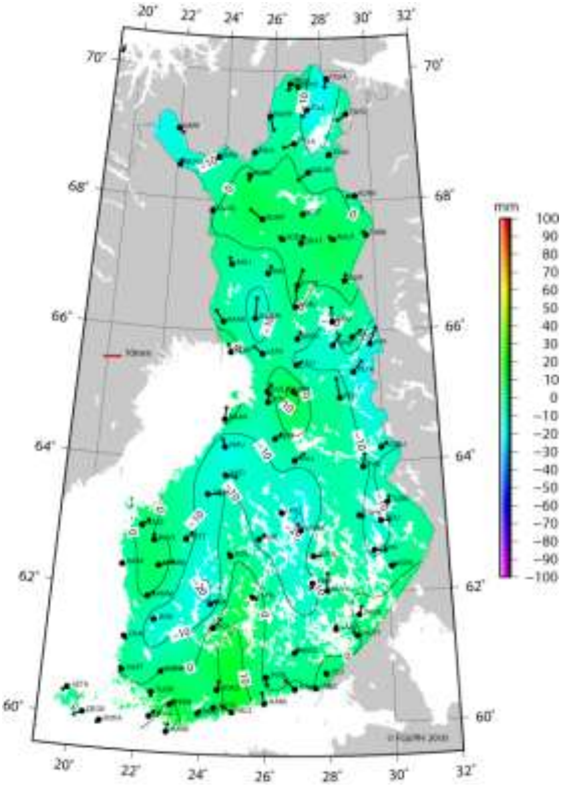
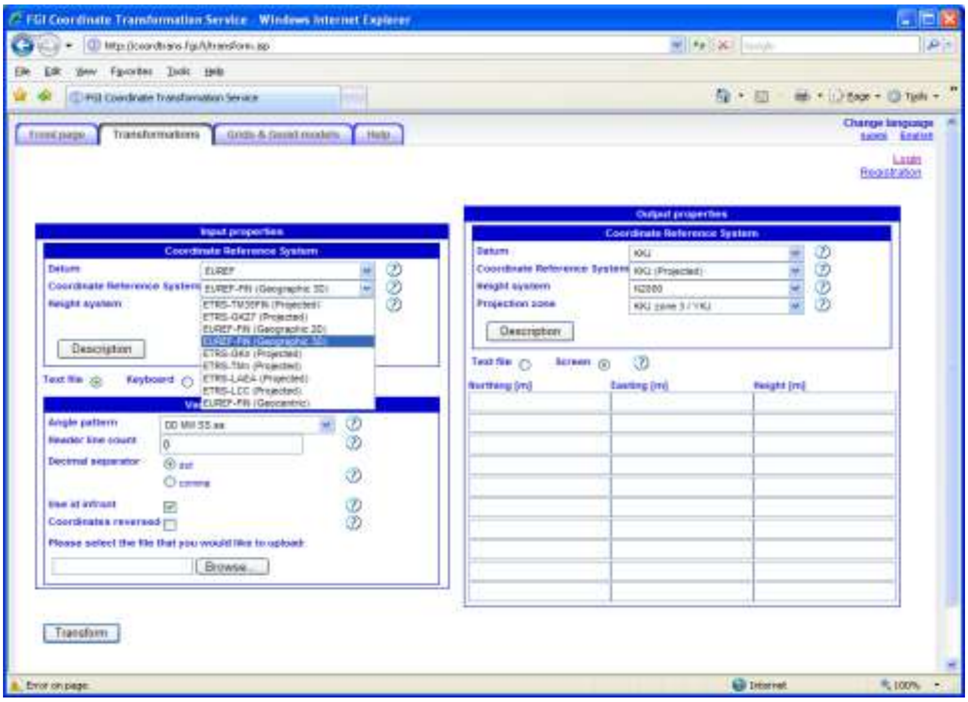


**Figure I-10.** Accuracy of NKG transformation when intraplate deformations have been taken into account with NKG_RF03vel model (horizontal residuals shown with vectors and vertical residuals with colour map).



Input properties

Coordinate Reference System

Datum: EUREF
Coordinate Reference System: EUREF-FIN (Geographic 3D)
Height system:

ETRS-TM35FIN (Projected)
ETRS-GK27 (Projected)
EUREF-FIN (Geographic 2D)
EUREF-FIN (Geographic 3D)
ETRS-GKn (Projected)
ETRS-TMn (Projected)
ETRS-LAEA (Projected)
ETRS-LCC (Projected)
EUREF-FIN (Geocentric)

Text file ● Keyboard ○

Angle pattern: DD MM SS.ss
Header line count: 0
Decimal separator: ● dot ○ comma
Use id infront: ☑
Coordinates reversed: ☐
Please select the file that you would like to upload:

Output properties

Coordinate Reference System

Datum: KKJ
Coordinate Reference System: KKJ (Projected)
Height system: N2000
Projection zone: KKJ zone 3 / YKJ

Text file ○ Screen ●

| Northing [m] | Easting [m] | Height [m] |
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**Figure I-11.** Interface of the new web-based transformation service.

## 1.8 Web application for coordinate transformations

The new coordinate transformation service was launched in 2008. The service developed at the FGI enables clients to perform coordinate transformations between the Finnish national coordinate reference systems through a Web application (Fig. I-11).

The Coordinate Transformation Service includes all Finnish nationwide coordinate reference systems (i.e., the datums kkj and EUREF-FIN with the coordinate systems usually applied with them) including the height systems N60 and N2000. In addition to the nationally used coordinate reference systems, the service supports the ETRS-LAEA and ETRS-LCC coordinate reference systems to fulfil the transformation requirements arising as a consequence of the INSPIRE Directive.

The Coordinate Transformation Service permits to transform single coordinates or coordinate lists stored in ASCII files. The usage of ASCII files allows additional features, like the use of angles in diverse units, points having identifiers and storing the coordinate values in varying orders.

The downloadable material includes the FIN2000 and FIN2005N00 geoid models calculated by the FGI, the triangle-wise affine transformation between the kkj and EUREF-FIN and the triangle-wise height transformation between the N60 and N2000 height systems defined by the National Land Survey of Finland (NLS).

The service is also an information forum for datums, coordinate reference systems and transformations, with literature references, links and on-line publications. See http://coordtrans.fgi.fi/.

## 1.9 A historical documentary film about triangulation measurements

A historical documentary film concerning the triangulation measurements was prepared in 2007. The film illustrates the meaning and the methods of the measurements in a popularized way. The film was partly supported by a grant of the Finnish Cultural Foundation.

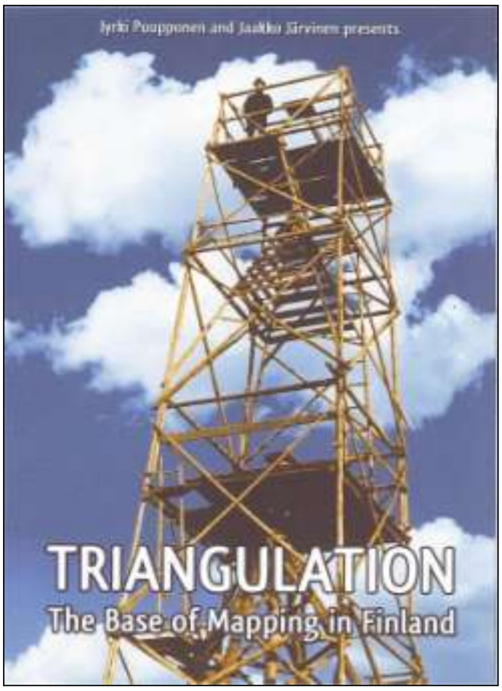

**Figure I-12.** Front cover of the history documentary film about triangulation measurements.

# II. Gravity Field

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## 2.1 Satellite gravimetry

The GRACE satellite has rapidly become a major tool in studying Earth dynamics by observing the associated changes in the gravity field of the Earth. Studies at the FGI have concentrated on two subjects: (i) the comparison of hydrological models in Finland with the variation in water mass deduced from variation in gravity as observed by GRACE, and (ii) the use of the variation in the water mass in the Baltic Sea to validate GRACE results. The two subjects are connected: the “leakage” of the continental water mass to the GRACE solution over the Baltic Sea must be taken into account, and vice versa.

In the hydrological study, monthly global gravity field models (in spherical harmonics) from GRACE were used to estimate the variation in the total water storage in the watershed area of Finland. The time series were compared to the time series of total water from the hydrological models GLDAS (Global Land Data Assimilation System), CPC (Climate Prediction Center) soil moisture, and WSFS (Watershed Simulation and Forecasting System). The WSFS of the Finnish Environment Institute (SYKE) is in operative use for prediction in a number of practical applications, and it is continuously controlled by hydrological observations.

A good agreement was found between the datasets and we conclude that GRACE estimates can reproduce the time series of total water in Finland (Fig. II-1).

For the Baltic Sea, the monthly water mass was estimated using tide gauge data. Steric corrections proved unimportant. Monthly global GRACE models in spherical harmonics, a local solution by the Ohio State University, and a local mascon model from GSFC (Goddard Space Flight Center) were used in the comparison. The GRACE models were able to recover 50...70% of the monthly variance of the Baltic fill level $0.16^2\,m^2$ (or $62^2 Gt^2$ in mass). Additional comparisons were made with altimetry, with the oceanographic model Wetehinen of the Finnish Meteorological Institute (Figure II-2) and with the OMCT background ocean model used in GRACE processing.

GRACE studies have in part been funded by the Academy of Finland (decision numbers 117094 and 116426).

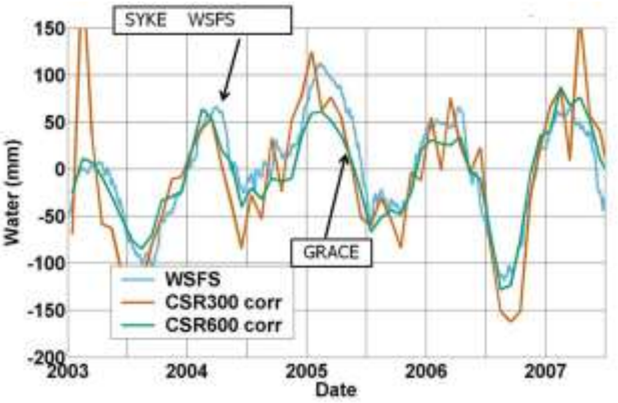

**Figure II-1.** Water storage in Finland estimated from the WSFS hydrological model and the CSR (Center of Space Research) GRACE model (RL04), with two different smoothing radiuses.

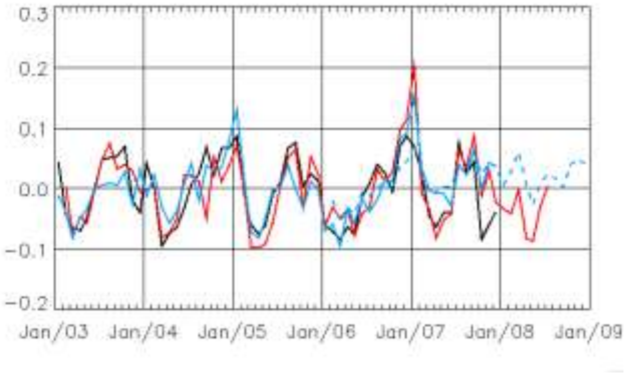

**Figure II-2**. Baltic fill level from monthly GRACE solutions (RL04) by CSR (black) and GeoForschungsZentrum (red), from tide gauges (solid blue), and from the model Wetehinen (dashed blue). The tide gauge and model results have been multiplied by 0.25 to make them consistent with the downscaling implicit in the GRACE solutions (400 km filter).

## 2.2 Geoid models

The gravity database of the FGI was screened in preparation for the calculation of a new gravimetric geoid model for Finland.

A local quasi-geoid model for Southwest Finland was calculated in co-operation with Prof. A. Ardalan of the University of Tehran. The overdetermined geodetic boundary value approach to telluroid and quasi-geoid computations, developed by Prof. Ardalan was used. This project is partially funded by the Academy of Finland (decision numbers 117132 and 212001).

The new national geoid model FIN2005N00 was published in the series of the FGI and implemented in the FGI Coordinate Transformation Service. The model can be used to transform EUREF-FIN ellipsoidal heights to normal heights in the N2000 system (Fig. II-3).

## 2.3 Absolute gravimetry

FGI has been engaged in absolute gravimetry since 1987, when the JILAg-5 was received from the Joint Institute of Laboratory Astrophysics (Colorado). The current absolute gravimeter FG5 no. 221 has been operational since 2003.

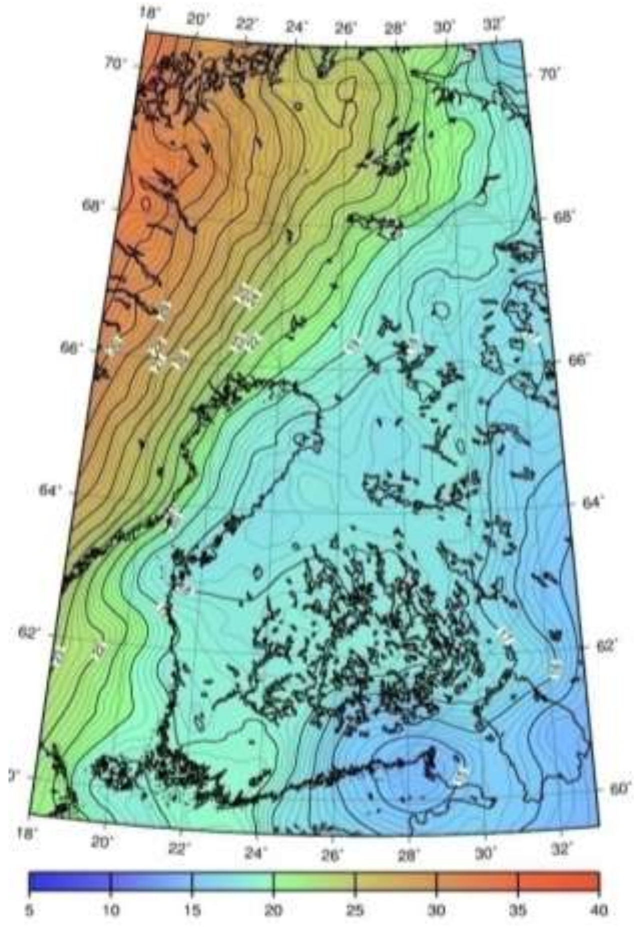

**Figure II-3.** The FIN2005N00 geoid model.

Regular absolute gravity (AG) measurements at the Metsähovi research station with the FG5 have been continued, typically once or twice per month. Altogether there are more than 80 occupations since 1988.

The Nordic Absolute Gravity Project was launched in 2003. It aims at maintaining time series of absolute gravity measurements at about 20 Nordic sites. The time series are compared with estimates of regional gravity change (due to the Fennoscandian PGR) obtained from the GRACE gravity satellite, with predictions from geophysical models of the PGR, and with vertical velocities determined by continuous GNSS and other methods. As a by-product, a highly accurate gravity reference network with estimates of gravity change rates is being produced. The project is coordinated by the Working Group for Geodynamics of the Nordic Geodetic Commission (NKG), as a part of the Nordic Geodetic Observing System (NGOS) of the NKG. In 2007–2010 FGI performed AG observations at 9 Finnish sites in addition to Metsähovi , altogether 20 station occupations (Fig. II-4).

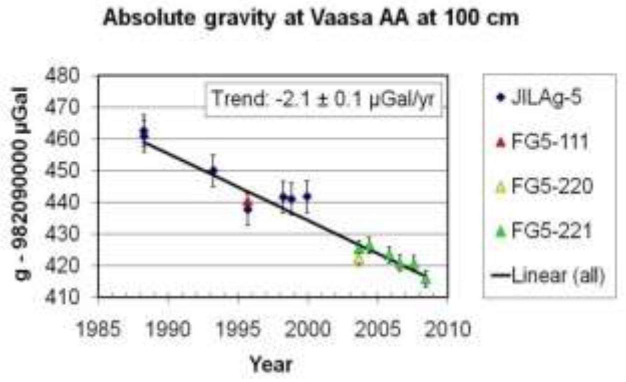

**Figure II-4.** Absolute-gravity measurements in Vaasa, Finland. The observed gravity rate agrees with the observed PGR vertical rate from GNSS at this site (about 10 mm/yr, depending on the frame adopted).

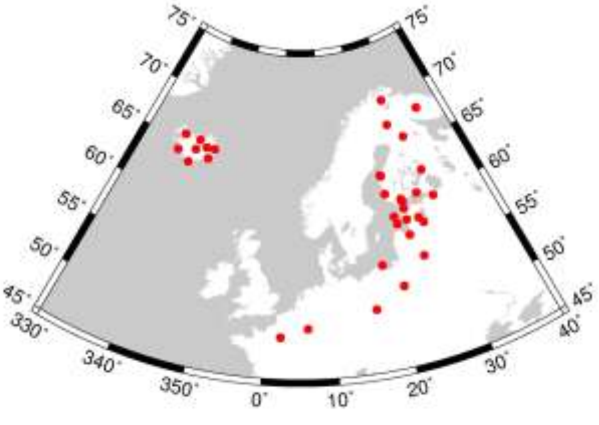

**Fig II-5.** Absolute-gravity sites occupied by the FGI in 2007–2010.

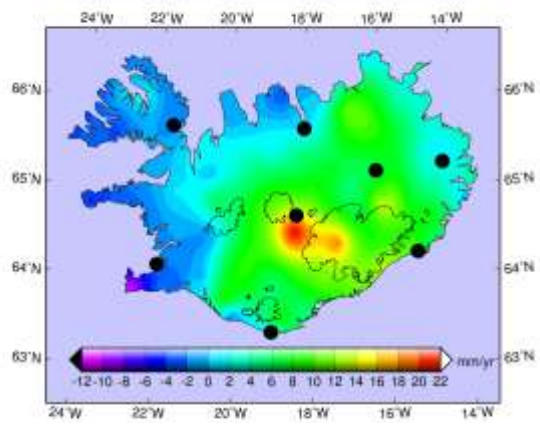

**Fig II-6.** Absolute-gravity sites occupied by the FGI in Iceland in 2007 in cooperation with the National Land Survey of Iceland (LMI). The background map shows the vertical rates in the frame IGb00, estimated by Valsson (2009) using the ISNET93 and ISNET2004 GPS-campaigns and continuous GPS stations.

Outside Finland the FGI has 2007–2010 measured absolute gravity points in Russia, Iceland, Poland, Lithuania, Latvia, and Estonia (Fig. II-5, Fig. II-6). These measurements were made in mutual co-operation projects. They serve both geodynamical studies and gravity standardization.

FGI is the National Standards Laboratory for acceleration of the free fall and the FG5 no. 221 is the national measurement standard. Metrological aspects are discussed in Chapter V.

## 2.4 Superconducting gravimetry

The superconducting (or cryogenic) gravimeter (SG) is based on the levitation of a superconducting sphere in a stable magnetic field created by current in superconducting coils. Depending on frequency, it is capable of detecting gravity variations as small as $10^{-11}$ ms$^{-2}$. For a single event, the detection threshold is higher, conservatively about $10^{-9}$ ms$^{-2}$. Due to its high sensitivity and low drift rate, the SG is suitable for the study of geodynamical phenomena through their gravity signatures.

The SG of the Finnish Geodetic Institute, GWR T020 has operated continuously at the Metsähovi fundamental station since August 1994, altogether over 16 years. The instrument is the oldest working SG installation in the world, without renovation. We have been able to continue its lifetime thanks to the support by Austrian colleagues who have kindly provided us with spare parts from the closed SG station in Vienna.

The SG at Metsähovi is a part of the Global Geodynamics Project (GGP) network. The GGP worldwide network consists of 31 stations (status 2010). The scientific goals of the GGP include seismic, geodetic and geophysical studies that range in frequency content from seismic normal modes, tides, core modes and wobble modes of the Earth to other long period variations in Earth’s gravity field such as tectonic deformation. The gravity data are sent to GGP data centre (http://ggp.gfz-potsdam.de) within six month after acquiring. In special cases, e.g. after a big earthquakes, data has been delivered immediately.

Recent studies at Metsähovi have largely concentrated on hydrology. After corrections for known time-variable gravity effects, such as tides, atmosphere and the Baltic Sea are made, the remaining gravity residual (80 nm$^{-2}$ peak-to-peak 1994–2010) is mostly due to (seasonal) variation in terrestrial water storage.

The hydrological effects in gravity can be crudely thought of as consisting of a local, a regional and a continental/global component. For the local component only the Newtonian attraction matters, while for the regional and continental/global contribution the deformation of the Earth is important too.

For modelling the regional and global contribution to gravity at Metsähovi, we have used the previously mentioned regional model WSFS and the global models CPC and GLDAS in various combinations. The time series of gravity computed from these models differ in scale but show approximately the same kind of phase pattern where the seasonal variation dominates.

Now, nearly any indicator of local water storage, say, groundwater level reproduces almost the same pattern. Therefore, it is not possible to distinguish between the local contribution and the regional/continental contribution in the SG record using statistical arguments only. If we want to use the SG for discriminating between different regional/continental hydrological models, or for validating GRACE observations, the attraction of local water storage must be physically modelled independently of the SG record. Recently we have been building up the observational base for this.

From the beginning (1994) the station has been equipped with two borehole wells in the crystalline bedrock. The building stands on bedrock and sediment layers were removed to 5...10 m distance from the walls as well. The remaining sediments are thin (0.2 to 4 meters within 100 m) but geologically quite complex. In 2006 two arrays of Time Domain Reflectometer (TDR) sensors of soil moisture were installed by the Finnish Environment Institute at 30 m from the SG.

In 2008–2009 several new instruments were installed within 100-150 m distance from the SG. The Technical University of Helsinki (now the Aalto University) added ten more TDR arrays. They consist of 5 sensors each at different depths. Soil resistivity is measured in a 20× 20 m$^2$ grid of 21×21 = 441 probes. For observing groundwater level in the sediments, 11 access tubes were lowered down to the bedrock surface in 2009 (Fig II-7).

For radiometric measurements of soil moisture content and soil density we established 5 dry access tubes: they provide in-depth profiling, and a calibration control for the TDR sensors. Soil samples have been taken from all sites and in a grid between them. In addition, weather information is recorded: precipitation, wind, and humidity. We measure regularly the thickness and the water equivalent of the snow cover around the station.

**Figure II-7.** Installation of the groundwater access tubes in 2009. Note the very short perforated section at this site, designed for the thin layer of ground moraine below silt and clay. (Photo: Jaakko Mäkinen)

Some first results from the new sensors are presented in the 4 plots in Fig. II-8. In the top plot the black curve shows the gravity residual of the SG T020, the red curve shows the gravity influence of variation in global continental water storage using the model GLDAS, the blue curve shows the total water storage (TW) in Finland from the WSFS, and the green curve shows the groundwater level in the local borehole well (BH) in bedrock. The TW and the BH have been transformed to gravity units using a least-squares fit to the gravity residual.

The TW and BH in the plot thus represent attempts to use the time series of a single hydrological index to account for the multiple-scale (local/regional/continental/global) hydrological influences on gravity. We found that GLDAS, TW, and BH explain 57%, 63%, and 38%, respectively, of the variance (17.8 $\mathrm{nms}^{-2})^2$ of the gravity residual. The corresponding rms "residual of residual gravity" is 11.7, 10.9, and 14.0 $\mathrm{nms}^{-2}$, respectively.

The second plot from top shows water levels in two groundwater tubes in soil. The T6 (black curve) is 100 m from the SG. The height is relative to the SG sensor. The T11 (red) is 200 m from the SG in the opposite direction from T6. The plotted water height relative to the SG sensor has been shifted by +4.5 m. Both tubes are in ground moraine below nearly-impermeable silt and clay layers. Note the much more rapid reactions of T6 and T11 to rainfall events (bottom plot) and to snowmelt (April 2010), compared with BH. Note also the minor differences between the tubes, possibly due to the different distance to recharge areas. Tube T6 was dry from July to September 2010 and tube T11 was frozen in winter 2009–2010.

The second plot from bottom shows the volumetric soil moisture content from two TDR sensors. SM1 (black) and SM2 (red) are 30 m from the SG. SM1 measures the soil moisture between 0.1 to 0.3 m depth and SM2 between 0.3 and 0.5 m depth. The nominal calibration used here exaggerates the soil moisture content during saturation events.

The bottom plot shows the daily precipitation at Metsähovi, in millimetres. Snowfall counts as water but is not well captured by the sensor.

Comparison of precipitation with soil moisture and groundwater observations demonstrates that in the summer a large pulse of rain is needed, preferably in a pre-wetted ground, to make any impression on the soil moisture, let alone on groundwater. This is because the strong summer evapotranspiration removes the water before it percolates into the deeper layers. The hydrological work with the SG was partly funded by the Academy of Finland (decision number 117094).

## 2.5 The First Order Gravity Network

The First Order Gravity Network (FOGN) of Finland was first measured by A. Kiviniemi in 1962 with the relative gravimeter Worden Master No 227. The network consisted of 41 stations. To quote Kiviniemi: ”For easy access, the first order stations are placed as near as possible of traffic junctions. In order to ensure the permanence of the stations, they were attached to monumental buildings, in most cases churches. When no suitable buildings were available, the stations were placed on levelling benchmarks”. Nearly all stations are outdoors and accessible at any hour without prior arrangements.

The internal accuracy was estimated to be 0.03...0.06 mGal (one-sigma). The current gravity values for the stations derive from a local adjustment of the IGSN71 in 1971 where an additional traverse measured with the LaCoste (LCR) gravimeter G-55 in 1966 was incorporated. The resulting FOGN values have epoch 1963.0 and they are in the mean tidal system of the IGSN71. They have provided a consistent reference for gravity surveys in Finland. The survey results then all share this epoch and tidal system, independently of the year when the survey was actually performed. The results can thus be easily transformed to, say, 2000.0 and zero-tide for e.g. geoid computation.

The network was re-surveyed in 1988 with two LCR-gravimeters. The campaign confirmed the accuracy of gravity differences to be better than 0.035 mGal (one-sigma). Checks also show that the FOGN values agree with contemporary absolute-gravity measurements to 0.03 mGal rms after the system differences, i.e. the epoch and the treatment of the permanent tide are accounted for.

The renovation of the FOGN started in 2009. The old sites are retained and a few additional sites measured to fill gaps especially in Lapland. The outdoor absolute gravimeter A10-020 of IGiK (Institute of Geodesy and Cartography, Warsaw, Poland) is used, operated by M. Sekowski of IGiK.

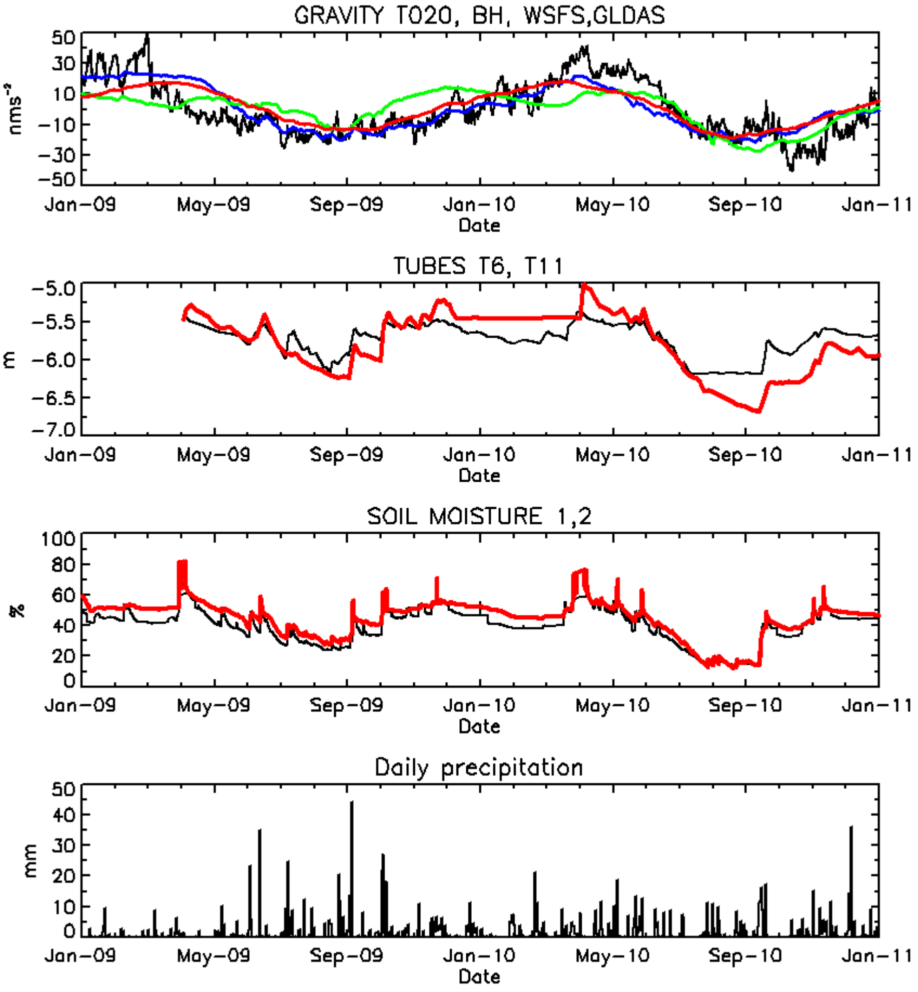

**Figure II-8.** Comparisons between the gravity residual from the SG GWR T020 at Metsähovi, and various hydrological and meteorological time series 2009–2010. All explanations and comments are in the text.

The work with the A10-020 was performed 2009–2010 (Fig. II-9, II-10). Altogether 51 field stations at 47 sites were occupied, all in two independent setups in opposite azimuths. From the difference of the setups the repeatability of their mean is better than 4 µGal. Maximally two stations could be observed in one day. As a control, 9 Finnish absolute gravity stations were occupied with the A10-020 altogether 25 times. From preliminary computations, the offset of the A10-020 relative to the FG5-221 absolute gravimeter of the FGI was negligible and the rms difference was 3 µGal. The length and frequency standards of the A10-020 were calibrated before and after the surveys at MIKES (Finnish Centre for Metrology and Accreditation).

The work at a station is not complete with just the A10 measurement done. A separate support expedition measures the vertical gradient of gravity, performs relative-gravity ties when the FOGN and A10 stations are not identical, does levelling to a bench mark, determines coordinates using RTK-GPS and tacheometer, and documents the station in photos and sketches. Around one day per absolute station is needed for these supporting measurements, slightly more or slightly less depending on the amount of relative gravimetry needed and on the levelling distance to the nearest bench mark. The supporting measurements will be completed in 2011.

Most FOGN stations are on massive stairs. The stairs cause a markedly non-constant vertical gradient of gravity. The users that visit the FOGN sites have relative gravimeters with different sensor heights and mount them on tripods of their own choice. Therefore the gradient measurements are performed using three levels, and the final gravity value will be published as a (non-linear) function g = g(z) of elevation z above station.

The gravity values of the 35000 stations in the National Gravity Net of the FGI will be recomputed with reference to the new FOGN values.

## 2.6 Relative gravimetry

No regional gravity surveys were performed by the FGI during the review period. Extensive high-precision relative work (i.e., vertical gradients and ties to excentres) was done to support absolute gravity measurements and the measurement of the First Order Gravity Network (cf. Section 2.5). The work on the Masala–Vihti calibration line is described in Section 5.3.

**Figure II-9.** The A10-020 at the station Turku Vartiovuori. Note the transportable benches and weights to mount the tent on stairs. (Photo: Jaakko Mäkinen)

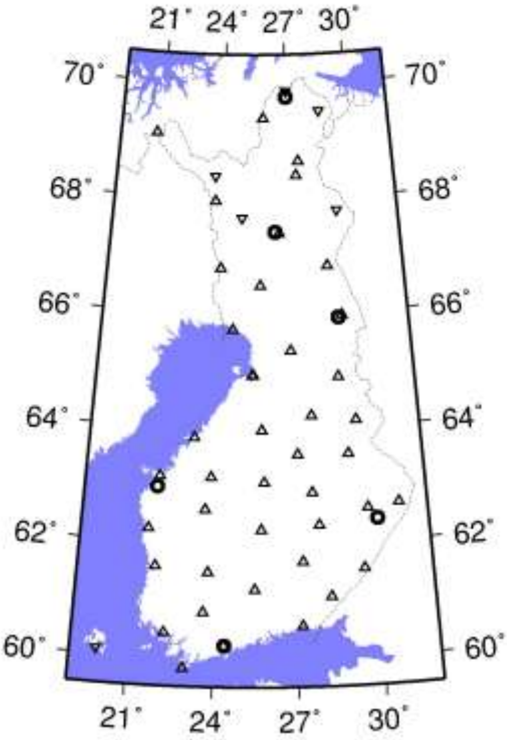

**Figure II-10**. Sites occupied with the A10-020 in 2009–2010. Triangles pointing up show old FOGN sites, triangles pointing down show new FOGN sites, and open circles show laboratory-type sites for comparison with FG5-221 measurements.

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# III. Geodynamics

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## 3.1 Glacial Isostatic Adjustment

The Finnish Geodetic Institute has been studying post-glacial rebound since the 1930s when the first reliable map of contemporary PGR rates inland was derived by FGI for Southern Finland from the difference between the Second and the First levelling of Finland. This and several later land uplift maps by FGI have been used for many geodetic and geophysical purposes.

The land uplift map that is presently used for standardization purposes in geodesy in the Nordic countries (cf. Chapter 1) is the NKG2005LU (Fig. III-2).

A project DynaQlim (Upper Mantle Dynamics and Quaternary Climate in Cratonic Areas) continued under the International Lithosphere Program (ILP). As a multidisciplinary, large international program, its aim is to improve our understanding on the relations between upper mantle dynamics, mantle composition, its physical properties, temperature and rheology. It is also meant to study Glacial Isostatic Adjustment (GIA) and ice thickness models, Quaternary climate variations and Weichselian glaciations during the late Quaternary. FGI is the coordinator of the project. An international workshop was arranged in Finland in 2009.

FGI scientists participate in the COST Action ES0701: Improved Constraints on Models of Glacial Isostatic Adjustment. Absolute-gravity results in Fennoscandia and the Antarctic were compiled and analyzed. GPS data in Finland and the Antarctic was provided to the global recomputation within the Action.

**Figure III-1.** Participants of joint DynaQlim-GGOS meeting in Espoo, Finland, in 2009. (Photo: Markku Poutanen)

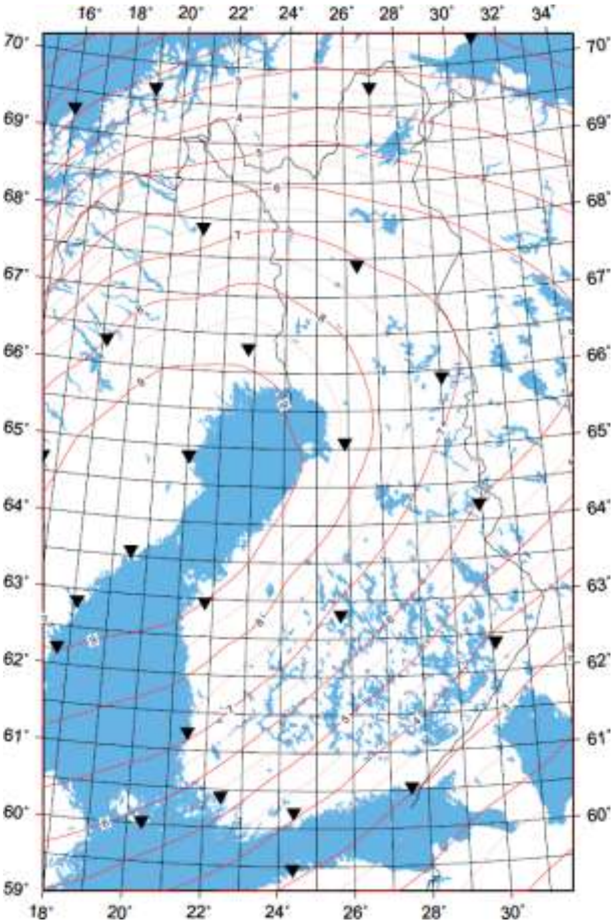

**Figure III-2.** Postglacial rebound in Finland (in mm/yr) according to the Nordic land uplift model NKG2005LU, here plotted in the version NKG2005LU_ABS, i.e. relative to the centre of mass of the Earth in ITRF2000. Triangles are the permanent GNSS stations.

## 3.2 Local deformation studies

The Finnish Geodetic Institute has studied crustal deformations in co-operation with the Posiva Oy. The studies started in 1994, when a network of ten pillars for GPS observations was established at Olkiluoto. The network was expanded in 2003 and in 2005. The Finnish Geodetic Institute, the Geological Survey of Finland, Posiva Oy and the Cities of Pori and Rauma started

GeoSatakunta project in 2002 in order to increase understanding of the unique bedrock of the area.

In 2008–2011 we have continued the repeated GPS measurements in four local deformation monitoring networks: in the Olkiluoto network twice a year and in the Kivetty and Romuvaara networks every two years. The GeoSatakunta network was last measured in 2008 and the next measurement is planned in 2011.

In Olkiluoto we have also measured a 511 m long baseline between the pillars GPS7 and GPS8 with the precise electronic distance measurement (EDM) instrument Kern ME5000 Mekometer in connection with the GPS measurements. According to nine years of data, the GPS gives, on the average, 1.3 mm longer distances than the metrologically traceable EDM. The reason for the difference is thought to be unmodelled or mismodelled offsets in GPS observations (e.g. ionosphere or troposphere effects or antenna phase centre related reasons). The trends in the EDM and GPS distance time series are similar.

All data of the 28 GPS campaigns in Olkiluoto since 1994 were reprocessed with a new processing strategy using antenna calibration corrections (see Chapter 5.4). The results were analysed by computing the change rates of the baselines and estimating horizontal velocities for the pillars using the barycentre of the velocities as a reference. In the inner part of the Olkiluoto network 80 percent of the change rates were smaller than 0.10 mm/a. Roughly one fourth of the change rates could be considered statistically significant (change rate larger than 3σ, with the maximum change rate 0.21 ± 0.03 mm/a).

The maximum change rates of the vector lengths from the 18 campaigns of Kivetty and Romuvaara networks were less than 0.2 mm/a. In Kivetty, one third of the change rates could be considered statistically significant but in Romuvaara none were significant.

The control reserve markers of the GPS pillars in Olkiluoto were measured every three years, last in 2010. After four control marker measurement campaigns we can now estimate the reproducibility of our angle and distance measurements. The standard deviations of horizontal angles, height differences and distances were 0.0028 gon, 0.0007 m and 0.0005 m, respectively. No movements of pillars have been found within the observing accuracy.

The Olkiluoto GPS network was levelled every two years, last in 2009. Some micronetworks at the construction sites in Olkiluoto are levelled every year and the connection to the national precise levelling network at Lapijoki every four years, last in 2007.

The GeoSatakunta GPS network was established in 2003 to obtain information on possible crustal deformations in the Satakunta region. The network consists of 13 concrete pillars for episodic GPS campaigns and the Olkiluoto permanent GPS station. The vector lengths range from five to 65 km.

We processed the GPS data of three annual campaigns each year 2003–2008 using Bernese 5.0 GPS software. Typically, the length of a vector varied from campaign to campaign less than 2.0 mm (peak-to-peak) without any evident trend. Estimated velocities were small (< 0.2 mm/a) and in most cases statistically not significant because of the relatively short time series. More campaigns are needed, especially to determine the deformation in the southern part of the network where time series are shorter. However, it is not necessary to carry out measurements as frequently as three times per year.

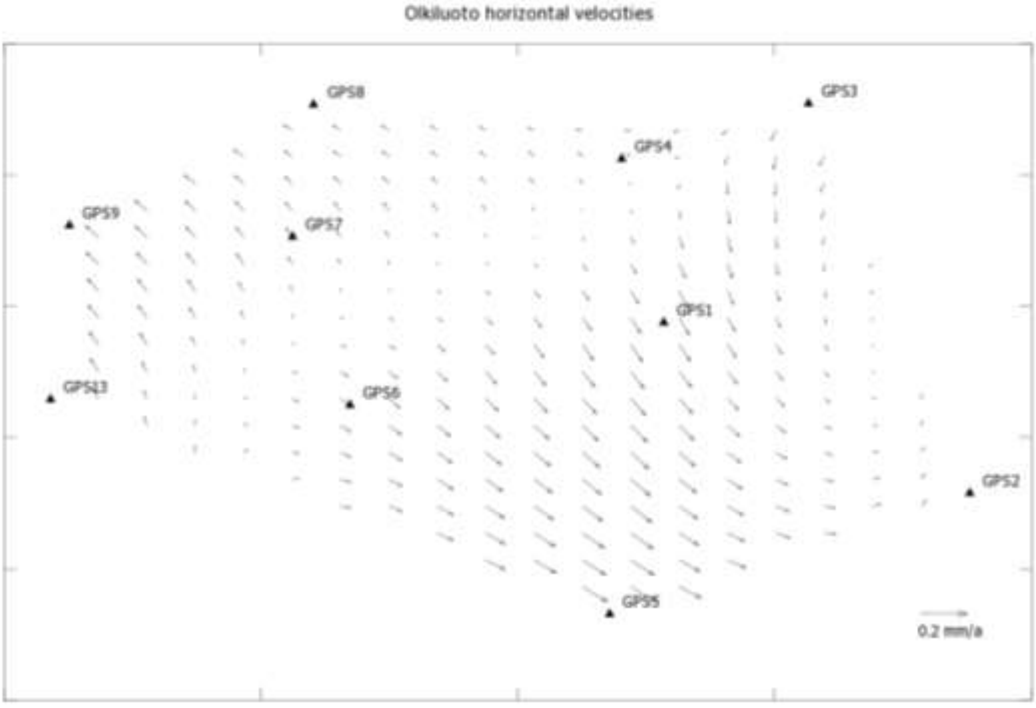

**Figure III-3.** Horizontal velocities in the Olkiluoto network.

**Figure III-4**. The GeoSatakunta GPS network. (Base map © National Land Survey, license 51/MML/09)

## 3.3 Long interferometric water-tube tiltmeter

The interferometric water-tube tiltmeter (WT) of the FGI was described in “Geodetic Operations in Finland 2004–2007”. In the autumn 2007 a WT with a 50.4m tube was installed in north-south orientation (NSWT) in a tunnel of the Tytyri limestone mine (60°16’N, 24°05’E) near the town Lohja in southern Finland. Great care was taken to install the whole tube horizontally, not just the two end vessels. The mine is active but the NSWT is in an inactive part 160 m below ground level. The recording computers are at 200–260 m distance from the tube to avoid thermal influences. The northern end of the NSWT is shown in Fig. III-5.

First results from the new NSWT are very promising. From 187 days of data, the main tidal waves could be solved with the same precision as from the earlier north-south tube with 1172 days of data.

From the NSWT recordings the toroidal free oscillations after the Chilean M = 8.8 earthquake (February 27, 2010) were analysed. Similar toroidal oscillations were seen after the Sendai earthquake (March 11, 2011) in Japan. Observed toroidal oscillations agreed well with the free oscillation model values given by Masters and Widmer (1995).

Loading by the Baltic Sea gives a strong N-S tilt signal at the NSWT located 30 km north from the coastline of the Gulf of Finland (Baltic Sea). In Fig. III-6 the observed tilt is compared with the tilt computed using tide gauge data on the Baltic level, and the NLOADF program package by Agnew (1997).

**Figure III-5**. The Fizeau-Kukkamäki liquid level interferometer in the north end of the NSWT. (Photo: Hannu Ruotsalainen)

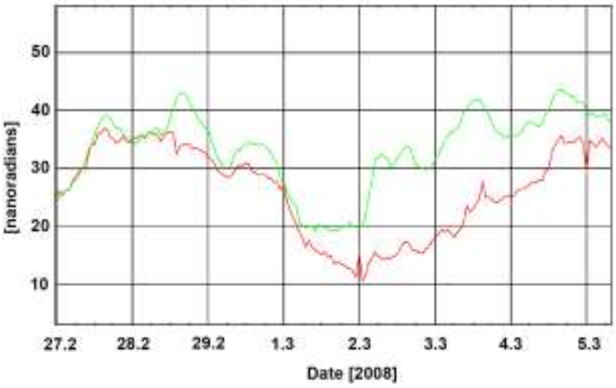

**Figure III-6**. Non-tidal tilt due to the Baltic Sea load computed from tide gauge observations (upper curve, green), and visible in the de-tided tilt record of the NSWT (lower curve, red).

## 3.4 Antarctic science

The FGI has participated in Antarctic research since 1989, performing the field work under the auspices of the Finnish Antarctic Research Program FINNARP. Currently the FGI maintains a time series of absolute gravity and GNSS measurements in Dronning Maud Land. The absolute-gravity sites at the stations Aboa (Finland), Sanae IV (Republic of South Africa) and Novolazarevskaya (Russia) were last occupied in the season 2005/6.

The continuous GPS station at Aboa (73°03' S, 13°24' W) is operating since January 2003. Aboa is a summer station only. The GPS data is recovered annually by the FINNARP summer expeditions and the rest of the time the receiver is operating unattended, without communicating with the outside world. With the exception of a gap in data in 2006 due to software failure the operation has been successful. At Sanae IV we have relied on the IGS station VESL and at Novolazarevskaya on GNSS epoch campaigns by SCAR and by ourselves.

The purpose is to detect the gravity change and deformation of the solid Earth due to PGR and to changes in present-day ice mass balance of the Antarctic. The time series of vertical position at Sanae IV and Aboa are shown in Fig. III-7. There is an apparent regional uplift during the period shown that is not accounted for by the PGR models. It is thought to be due either to variation in contemporary ice mass, or to reference frame problems in the GNSS data.

## 3.5 Crustal loading in vertical GPS time series

The effect of the atmospheric pressure loading, the effect of the non-tidal Baltic Sea loading and the effect of continental water loading was studied at seven GPS stations in Fennoscandia using monthly averages. Three sites close to the Baltic were selected for closer scrutiny. Removing the total computed loading from the GPS time series reduced the standard deviation, and for short series also influenced the trend determined.

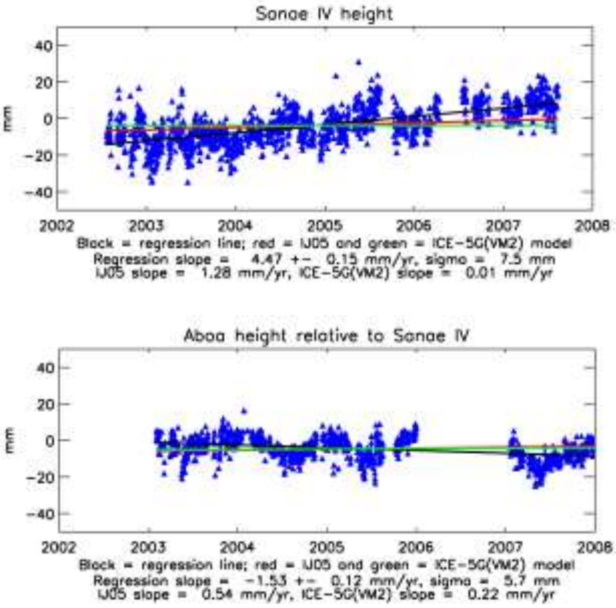

**Figure III-7.** Top: daily time series of vertical position from GPS in ITRF2005 at Sanae IV (VESL) from ftp://sideshow.jpl.nasa.gov/pub/mbh/point/ (2010-10-27). Bottom: daily time series of vertical position from GPS at Aboa relative to VESL, our processing with Bernese software. Both plots show the trend computed with formal standard error (1-sigma), and the trend expected from two PGR models, the IJ05 by Ivins and James (2005) and the ICE-5G(VM2) by Peltier (2004). Comments in text.

Three different models (WGHM, CPC, LaDWorld) were used to compute the hydrological load but the GPS series did not show clear preference for any of them. While the Baltic signal was considerable (Fig III-8), it did not decrease the standard deviation of the GPS time series correspondingly. This is not presently understood.

At the three stations analyzed, removing the seasonal variation decreased the standard deviation of the monthly GPS solutions by maximally 40%. The seasonal variation in GPS tended to underestimate the seasonal variation in modelled load.

The work was partly funded by the Academy of Finland (decision number 117094).

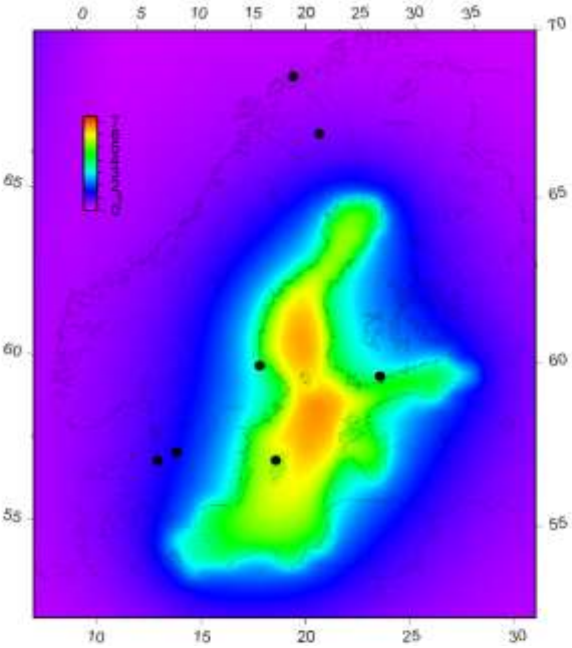

**Figure III-8.** Vertical deformation caused by the Baltic high water in March 2006, as calculated from tide gauge data (monthly means), in mm. The solid circles show the GPS stations studied.

# IV. Positioning and other applications

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## 4.1 GPS quality

In the past decade new real-time GPS measurement methods have become more and more common. However, traditional static GPS surveying is still the most accurate and reliable GPS method and should be utilized to e.g. measuring of benchmarks. Even if the static GPS measurements have been used for precise surveying over two decades, consistent information about relation between accuracy, baseline length and observing time has been difficult to acquire and the information has varied depending on a source. The outcome of this study gives relation between these factors.

The study was conducted using commercial GPS software with default processing parameters, covering observing sessions between 10 minutes and 24 hours and baselines between 0.6 km and 1,069 km. Over 10,000 baselines were processed using broadcast and precise ephemerides. The set of data used in the study is a random sample chosen from several GPS campaigns. This way it was to give a realistic picture of accuracy by averaging e.g. the influence of atmosphere and satellite geometry. The accuracy is presented for individual baselines i.e. adjustments were not applied. A series of fitting schemes were tested over the data and the one with the best fit was chosen.

The final result is given as an easily readable graph presenting the relation between the accuracy, baseline length and observing time (Figure IV-1). Using the graph one may optimize the observing times and thus increase productivity of static GPS surveying.

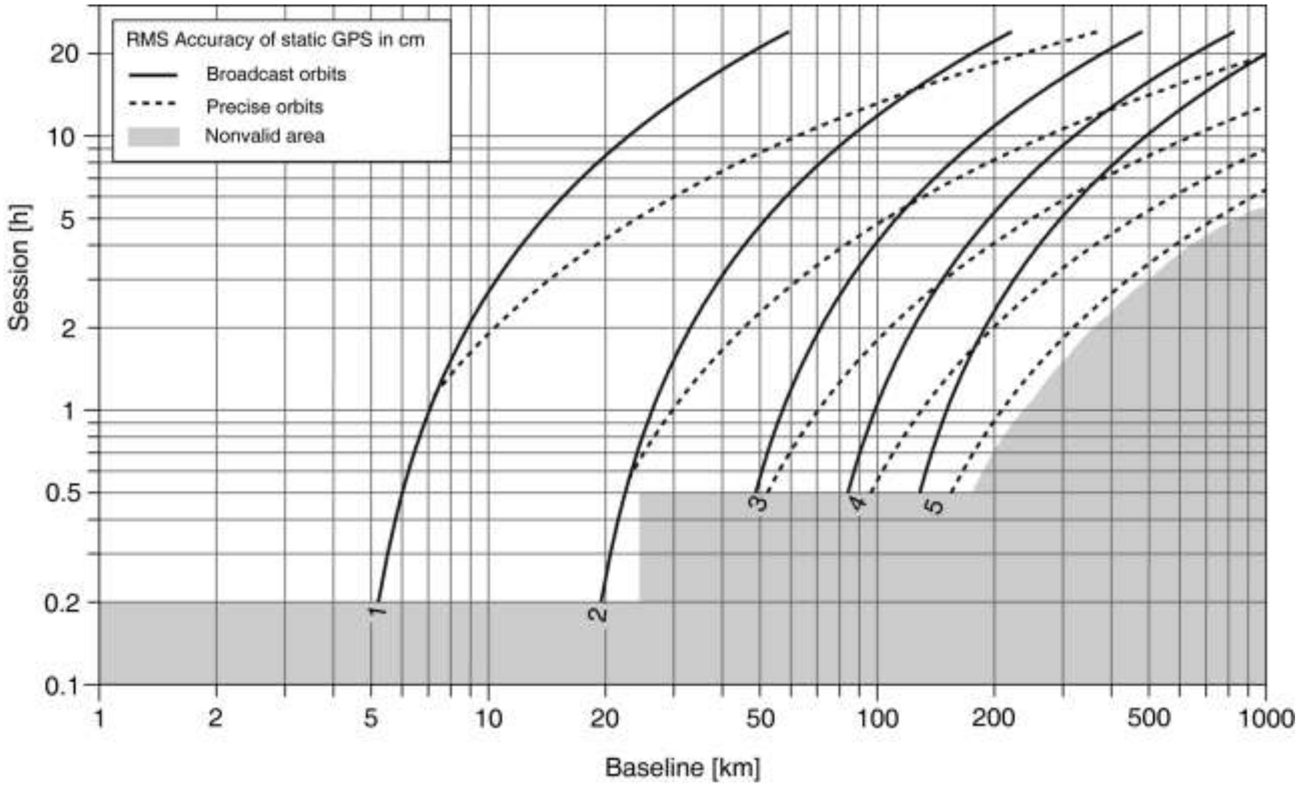

**Figure IV-1.** Static GPS results for individual baseline solutions with broadcast and precise ephemerides. Dependency of baseline length, observing time and accuracy (rms) is given with regression lines 1-5 cm. For geodetic measurements one should use accuracy better than 2 cm, and choosing it depending on quality and reliability requirements.

## 4.2 Quality of Virtual Reference Station (VRS) observations

Networking GNSS reference stations enable real-time bias estimation to improve e.g. real-time kinematic measurements. One approach is Virtual Reference Station (VRS) in which VRS observations (virtual data) are generated from the network to virtual position within the network coverage. Several studies have shown that bias estimation expands the area of operation and increases reliability and accuracy in real-time positioning. However, a major disadvantage of VRS concept is that virtual data does not include any information of its accuracy and the quality has to be verified on statistical basis. The FGI studied temporal and spatial quality of virtual data by quantifying quality with accuracy of zero-baselines between virtual and real data at same position.

Temporally, long-term quality was evaluated with 10-month-long time series of virtual data. Time series show that virtual data has good repeatability. Daily repeatability is 2 mm for horizontal components and 5 mm for up component, being quite equal for all stations. However, some biases remain to the results, especially in up component (Figure IV-2). Average of up component from time series varies from -37 mm to +21 mm and seems to be spatially correlated (one station in South-East Finland differs from the pattern and is probably due to some problems in adjustment of VRS network coordinates).

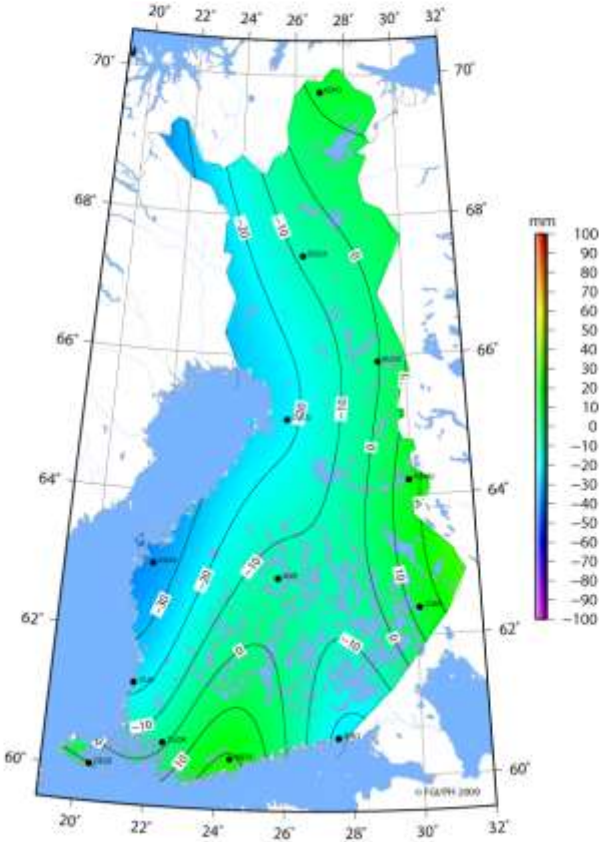

**Figure IV-2.** Spatial accuracy of VRS observations, up component (mm).

In order to estimate the reason for the spatial bias, we investigated the coordinates of the reference stations (of the VRS network). In addition to current network computation procedure (processing the coordinates directly in EUREF-FIN reference frame), the coordinates of the reference stations were processed also in ITRF2000 and transformed to EUREF-FIN by taking into account intraplate deformations caused by PGR with NKG method. Accuracy (rms) of this transformation is better than 1 cm. Resulting coordinates were compared to the ones computed in EUREF-FIN.

The comparison implies that the bias seen in virtual data relates to reference station coordinates. Nordic reference frames deform in time due to postglacial rebound that makes accurate determination of station positions challenging in the Nordic countries. EUREF-FIN has deformed already approx. 10 cm at the west coast of Finland by the PGR since its reference epoch 1997.0 to the epoch of the study (2006.5). At the SE part of country the deformation is less than three cm. When a GPS solution (network) is adjusted by fixing the coordinates in such frame, the solution becomes distorted and influence of PGR is seen (indirectly) in virtual data through the imprecise reference station coordinates.

## 4.3 EGNOS and its RIMS station in Finland

### Background

The use of positioning satellites is nowadays critical to, for example, air, maritime and automotive traffic. An essential part of a Satellite Based Augmentation System (SBAS), which provides a differential positioning service through geostationary satellites, is the ground network of reference stations, which can relay information about the operating status of the positioning satellites and provide the range measurement corrections necessary for calculating a more accurate location than in standalone mode of operation. In Europe, a satellite-based augmentation system called EGNOS (European Geostationary Navigation Overlay Service) is used for providing augmentation to GPS (Global Positioning System) and GLONASS (Global'naya Navigatsionnaya Sputnikova Sistema) by reporting on the reliability and accuracy of the signals. The differential corrections provided by the EGNOS system can improve the satellite positioning accuracy to a couple of meters.

### EGNOS

EGNOS is a European SBAS consisting of three GEO (Geostationary Earth Orbit) satellites and a network of Ranging and Integrity Monitoring Stations (RIMS), Mission Control Centers (MCC), and Navigation Land Earth Stations (NLES) for ground control. The EGNOS system provides the end users with additional ranging data from GEO satellites, differential corrections, and integrity information.

### The Ranging and Integrity Monitoring Station of EGNOS in Finland

Since 2003, the FGI has maintained, in cooperation with the European Space Agency (ESA) and the European Satellite Services Provider (ESSP), the only EGNOS RIMS station in Finland. Because the station is located in a marginal area for the EGNOS service coverage (60 km south of Lappeenranta), it is one of the most important stations in the whole system. In Finland, if there was no RIMS station in Virolahti the accuracy of the EGNOS service would be significantly lower. In addition, FGI maintains a permanent GPS network in Finland. This FinnRef® network is part of the NGOS (Nordic Geodetic Observation System) network. Figure IV-3 presents the FinnRef® network and the location of the RIMS station in Virolahti, in the South-East of Finland. Figure IV-4 presents one of the antennas on the site of the RIMS station in Virolahti. The station tracks the GPS and EGNOS GEO satellites and sends the observations in real-time to the EGNOS MCC via a dedicated telecommunication link.

**Figure IV-3.** The FinnRef® network of permanent GPS stations (red circles) and the EGNOS RIMS station (green open circle) in GoogleEarth$^{\mathrm{TM}}$.

**Figure IV-4**. Antenna site at the EGNOS RIMS station in Virolahti. (Photo: Tomi Tenhunen)

### EGNOS performance in Finland

The current EGNOS performance in Finland is not as good as that in the central Europe. The major reason for the unsatisfactory performance is due to the fact that Finland is located in the North-East boundary of the EGNOS service area. In addition, the EGNOS satellites are very low in elevation in Finland and therefore they are difficult to being tracked and their differential corrections to being obtained.

In order to access the EGNOS service, the end user needs the line of sight to at least one GEO satellite. This is not a problem at all for aviation and maritime applications even in the regions at high latitudes because an open sky is always available for such applications. However, an open sky is not always available for land applications because of the obstacles in the vicinity of the end users (e.g. in city canyons). The situation becomes worse for the regions at high latitudes because the elevation angles to the GEO satellites are rather low.

There are no pseudorange corrections for GPS satellites rising from the East or North-East with low elevation angles because each satellite needs to be viewed by three RIMS stations from the ground in order to calculate the pseudorange corrections that EGNOS can pass on. Thus, as there are no RIMS stations on the East side of Finland, the visibility to the nearby RIMS stations for the satellites rising from East is poor, and there are limited pseudorange corrections available. Therefore, it is not possible to use the current EGNOS service in Finland for safety-of-life applications.

# V. Metrology and standardization

Jorma Jokela, Jaakko Mäkinen, Pasi Häkli, Hannu Koivula and Paavo Rouhiainen

Finnish Geodetic Institute

The Finnish Geodetic Institute is a National Standards Laboratory for two quantities, acceleration of free fall and length. The metrological research and measurements include measurements at the Nummela Standard Baseline, maintenance and development of the Väisälä interference comparator and the associated quartz gauge system, levelling rod and levelling system calibration, the national gravity network, absolute and relative gravity measurements, and continuous recording of temporal gravity variations with a superconducting gravimeter. The calibration services include instruments and systems used in height determination, geodetic baselines and electronic distance measurement (EDM) instruments.

The FGI is a member in the CIPM Mutual Recognition Arrangement (MRA) of national measurement standards and of calibration and measurement certificates issued by national metrology institutes. Requirements of the ISO/IEC 17025 ja ISO 9001 standards are implemented in the quality management system of the National Standards Laboratories, described in the quality manual. The quality manual was renewed in 2009 and 2011. In 2009, the FGI participated in the EURAMET TC-Q re-evaluation of the quality management system.

## 5.1 Standard baselines and calibration baselines

The Nummela Standard Baseline of the FGI was measured again with the Väisälä interference comparator in autumn 2007. The description of the latest measurements in 2005 and 2007 was published in 2010. The result of the 864 metres total length of the baseline deviates only +0.11 mm from the previous measurement in 1996, and +0.08 mm from the first measurement in 1947. The variation in the 15 measurements during 60 years has remained smaller than 0.6 mm. With the ±0.07 mm standard uncertainty the baseline still is the state-of-the-art world-class measurement standard in geodetic length metrology.

The EDM equipment was renewed by purchasing a new Leica TC2003 tacheometer equipment. The annual calibrations of the own instruments at the Nummela Standard Baseline include the two newest Leica TC2003 tacheometers and five prism sets of the FGI, and one Kern ME5000 Mekometer with a prism reflector, property of the Institute of Surveying Sciences in the Aalto University. The projection measurements between the underground benchmarks of the baseline and the calibration facilities on the observation pillars are performed at least twice during every field work season, which at the most lasts from May to November.

In 2008–2011 the FGI participated in the European Metrology Research Programme (EMRP) Joint Research Project “Absolute long distance measurement in air”. This project of nine European metrology institutes was partly funded by the European Community’s Seventh Framework Programme, ERA-NET Plus. The contribution of the FGI in this project was to utilize the Nummela Standard Baseline in testing and validation of new absolute distance measurement (ADM) methods, based on synthetic multi-wavelength interferometry.

The deliveries of the EMRP project included a scale transfer measurement from the Nummela Standard Baseline to the 1 080 m geodetic baseline of the Austrian metrology institute (BEV) in Innsbruck, in autumn 2008. A small indoor test field was concurrently measured for the University of Innsbruck. In autumn 2010 scientists from three European metrology institutes, CNAM (France), PTB (Germany) and MIKES (Finland) tested their newly developed equipment prototypes for ADM and refraction measurements at the Nummela Standard Baseline. The results are encouraging, in spite of the challenging field conditions.

The FGI measured the Vääna Calibration Baseline of the Estonian Land Board, Maa-amet, in autumn 2008. Maa-amet has thoroughly reconditioned the baseline since the previous measurements in 2000. The modern baseline now consists of 13 high-quality observation pillars for distances from 2 metres to 1 344 metres and a set of benchmarks in the ground.

Activities continued in autumn 2008 also at the Kyviškės Calibration Baseline of the Vilnius Gediminas Technical University (VGTU) in Lithuania. The FGI used the stable baseline and test field there to examine the scale of GPS measurements. The previous high-precision EDM results from 1997, 2001 and 2007 were used for comparison, complemented with new measurements simultaneously with the GPS measurements.

The measurements in Austria, Estonia and Lithuania were made with the same traceable scale transfer technique. The Kern ME5000 Mekometer, calibrated before and after at the Nummela Standard Baseline, was used as a transfer standard. The scale was transferred also to China, as two expeditions visited the Nummela Standard Baseline in summer 2009, from the Chinese Academy of Surveying and Mapping and from the Zhengzhou Surveying and Mapping Institute.

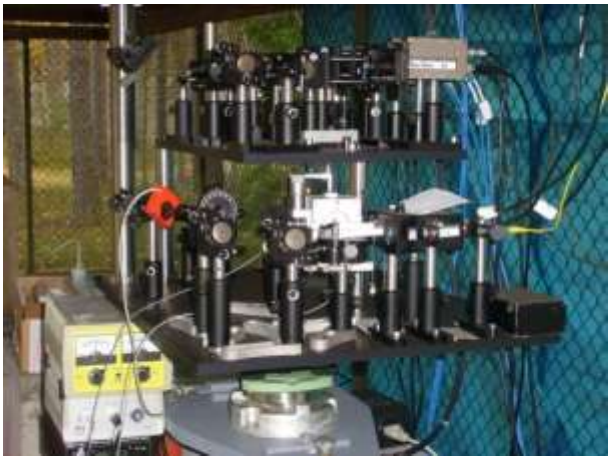

**Figure V-1.** A part of the new ADM equipment of the PTB on the zero pillar of the Nummela Standard Baseline. (Photo: Jorma Jokela)

**Figure V-2.** The halfway of the Nummela Standard Baseline. (Photo: Martin Rub)

**Figure V-3.** The geodetic baseline of the BEV in Innsbruck, Austria. (Photo: Jorma Jokela)

**Table V-1.** Number of calibrations made with the FGI rod and system calibration comparator.

| Year | Invar rods | Digital levels |
|---|---|---|
| 2007 | 40 | 32 |
| 2008 | 35 | 24 |
| 2009 | 27 | 16 |
| 2010 | 35 | 24 |

**Figure V-4.** The Vääna calibration baseline of the Estonian Maa-amet. (Photo: Jorma Jokela)

**Figure V-5.** The Kyviškės calibration baseline in Lithuania is ideal for also GPS metrology. (Photo: Jorma Jokela)

## 5.2 Calibration of levelling instrumentation

The FGI has constructed a horizontal-vertical rod-comparator/system calibration apparatus. In addition to the calibration of conventional and digital levelling rods, the system calibration of digital levels is performed in a fully automated fashion. In addition to calibrations for Finnish users, levels and rods were calibrated for China, Estonia, Iceland, Latvia, Lithuania and Sweden. Co-operation with the Chinese Academy of Surveying and Mapping (CASM) was started. Planning and construction of a modernized comparator is in progress.

## 5.3 Acceleration of free fall

The FGI is the National Standards Laboratory for the acceleration of free fall. The FGI maintains the national measurement standard (the FG5-221 absolute gravimeter), the national gravity reference station at the Metsähovi Geodetic Observatory, the Masala–Vihti calibration line for relative gravimeters, and the First Order

Gravity Net (FOGN). The work on the FOGN, the monitoring of gravity at Metsähovi, and some other aspects are reported in Chapter 2.

**Comparisons of absolute gravimeters**

FGI participated with the FG5-221 in the Seventh International Comparison of Absolute Gravimeters (ICAG-2005) at the BIPM (Sèvres, France) in September 2005, and in the European Comparison of Absolute Gravimeters in Walferdange (Luxembourg) in November 2007. The results of these comparisons were published in 2008. In both cases the result of the FG5-221 is close to the comparison reference value.

The ICAG-2005 was organized as a pilot study for a key comparison. The Eighth International Comparison of Absolute Gravimeters ICAG-2009 at the BIPM in September–October 2009 had two components: a key comparison and a pilot study. The FGI participated with the FG5-221 in the key comparison, which was the first-ever in gravimetry. The results will be published in 2011.

As a part of the ICAG-2009, the BIPM organized the relative gravity campaign RGC-2009, to measure the vertical gradients at the absolute gravity stations and the gravity differences between them. The FGI participated in the RGC-2009 with the relative gravimeter Scintrex CG-5 no. 31110052.

In association with the ICAG-2009, the BIPM also organized a campaign to map with high accuracy gravity as a function of 3-D location in the laboratory of the BIPM Watt Balance (WB) project. The WB project aims at determining the Planck constant *h*, to support the future realization of a new definition of the kilogram based on a fixed value of *h*. The FGI participated in the WB gravity campaign with the absolute gravimeter FG5-221 and the relative gravimeter Scintrex CG-5 no. 31110052.

In connection with the Nordic Absolute Gravity Project, regular bilateral comparisons of the FG5-221 with the FG5-220 of the Leibniz Universität Hannover (Germany) and with the FG5-233 of Lantmäteriet (Sweden) were organized in Metsähovi. A bilateral comparison with the FG5-110 of the Research Institute of Geodesy, Aerial Surveying and Cartography (TsNIIGAiK, Moscow) took place at two sites in Russia (Pulkovo, Lovozero) in 2007.

**Masala–Vihti calibration line**

The Masala–Vihti calibration line starts at the premises of the FGI in Masala and covers 53 mGal with a driving distance of 40 km. It is mainly utilized for calibrating relative gravimeters used in geophysical prospecting and in regional gravity surveys. The users can do this in self-service, measuring themselves and applying the published gravity values.

The absolute-gravity measurements at the end points were repeated in 2008. Multi-level measurements of the vertical gradient both at them and the 4 intermediate points were performed. We will publish updated values for all 6 stations, in the form $g = g(z)$ where gravity $g$ is a (non-linear) function of the height $z$ above the station marker. This is needed because at many of the stations the vertical gradient of gravity is markedly non-constant and the users have different instruments and use different tripod heights.

**Gravity vs. acceleration of free fall**

The FGI can issue a calibration certificate either for gravity or for the time average of the acceleration of the free fall at the user's site. Note that the two are conceptually different: gravity as it is implicitly defined in IAG resolutions and in the IAGBN Processing Standards has for many time-dependent phenomena a correction target that is different from the time average. For example, zero-tide instead of mean-tide for the tidal correction, IERS pole instead of current barycentre for the polar motion, standard atmosphere instead of time-average for the atmospheric influence. For technical – and many scientific – purposes the relevant quantity is the momentary or average acceleration of free fall.

Most users requesting a calibration certificate for the value of the acceleration of the free fall need it in a technical application where the uncertainty requirement is not very stringent, typically 1 ppm of gravity or 1 mGal. They are not interested in keeping track of the variation with time. The FGI then issues a calibration certificate for the time average of the acceleration of free fall with an uncertainty that is large enough to cover the variation with time.

However, for geodetic reference networks (for example, the work in Estonia mentioned in Section 2.3) it is the value of gravity that is required. The calibration certificates by FGI then include the definition of gravity. The uncertainty estimate includes the error sources influencing the estimation of the mean value of gravity during the station occupation.

## 5.4 GPS metrology

The FGI has performed GPS observations at the crustal deformation network in Olkiluoto, at a proposed disposal site for nuclear waste in Finland since 1995. Since 2002, a 511 m GPS baseline has been simultaneously measured using the Kern ME5000 Mekometer, the most accurate EDM instrument available, in order to control the scale of the network. A constant scale difference between GPS solutions and traceable EDM results was found in semi-annually repeated measurement campaigns, see Section 3.2. Since EDM results are accurate and traceable to the definition of the metre with well-defined uncertainties, this led to an assumption that the GPS solution is biased.

To study the problem, the GPS antennas were sent for individual absolute antenna calibration and additional EDM+GPS measurements were carried out at another length standard, Kyviškės calibration baseline in Lithuania. There we were able to compare several lengths between 20 m and 1 320 m in ideal conditions for GPS measurements, instead of only the single distance that can be measured in Olkiluoto. Traceable (true) lengths between the observation pillars were measured using a Kern ME5000 Mekometer as a scale transfer standard.

The ME5000 was calibrated at the Nummela Standard Baseline, a national standard of length in Finland.

The GPS data were processed in 24-hour sessions using individual and type-calibrated antenna tables, a local and global ionosphere model, three different cut-off elevation angles and several linear combinations and the results were compared with the EDM results. Analysis shows that the ambiguity resolution strategy and antenna calibration model play a significant role in GPS measurements compared to the cut-off elevation angle and ionosphere model.

The best metrological agreement was obtained with the L1 solution using an ionosphere model and individually calibrated antennas. The accuracy (rms) and maximum difference from true (EDM) values were 0.3 mm and 0.7 mm, respectively (Fig. V-6). However, a distance-dependency of 0.5 ppm, which was not seen in linear combinations, was evident for L1 and L1&L2 solutions. On the other hand, linear combinations with type-calibrated tables caused variations of up to 4 mm from the true value, even if high-quality choke ring antennas were used. With individually calibrated antennas, all solutions were within ±1 mm of the true value.

The study shows that individually calibrated antennas improve the accuracy of GPS solutions in metrological sense and that the best repeatability does not mean the best accuracy.

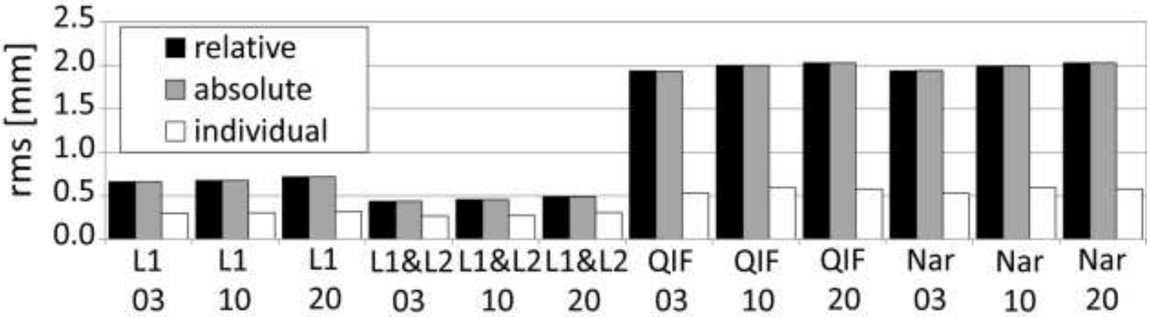

**Figure V-6.** The rms values of the different processing strategies using the global ionosphere model. The EDM results have been used as true values when rms values were determined. When type calibrated antennas (black and grey bar) were used, L1&L2 gives the best results. Linear combinations (Narrow-Lane and QIF) gave significantly worse accuracy but the best repeatability (not shown in the figure). When individual calibration values (white bar) were used, the rms values of all results decreased significantly but clear difference between non-combined results (L1, L1&L2) and linear combinations is still visible. In this case L1 gave the best result as a combination of accuracy, repeatability and distance-dependency (not visible in the figure). The ionosphere model or satellite cut-off elevation angle did not have a significant influence on the results.

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# VII. Geodetic Activities of the National Land Survey of Finland

Marko Ollikainen

National Land Survey of Finland

The NLS consists of 12 District Survey Offices, five national operational units and the central administration. At the beginning of 2010 two District Surveys Offices were joined. The NLS has staff about 2000, 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 assis-tance 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 proper-ty. They also supply cadastral information. The Offices gather and update data on the maps covering their areas for the topographic data-base.

NLS’s national operational units are responsible for development and research in their own areas, coordination of activities and nationwide services. The units are located in Helsinki as well as the central administration.

The NLS benchmark register contains informa-tion about control points and benchmarks. Most of these horizontal control points and levelling benchmarks are measured by the NLS. Some benchmarks measured by other agencies are also included.

Within the NLS, control surveys are carried out by South Finland District Survey Office. It is also responsible for maintaining the system of horizontal control points and benchmarks. The unit also provides expert and measurement ser-vices related to geodetic measurements and coordinate and height systems. The densification of the National networks was continued. The densification of the EUREF-FIN 2nd order network has been completed.

Promotion of the new reference frame has been done. NLS took EUREF-FIN coordinate system into use in 2010. NLS uses mainly plane coordinate systems ETRS89-GKn and ETRS89-TM35FIN in its activities.

The densification of the levelling network and re-levellings of some old levelling lines were continued. Preparations for using the new height system of Finland (N2000) were contin-ued. Adjustments of National Land Survey’s 2nd order levelling lines into the new height system have been finished. Adjustments of 3rd order levelling lines are still on-going. Transformation between N2000 and N60 (former height system) has been determined. Project to promote the new height system in NLS’s activities and products has been started.

# VIII. Gravity Operations of the Geological Survey of Finland

Seppo Elo

Geological Survey of Finland

Geological Survey of Finland (GTK) continued applying gravity measurements to bedrock research, to exploration of metallic ores and industrial mineral deposits, and to environmental studies. In 2009 GTK contracted Bell Geospace Ltd. to carry out trial AirFTG (Airborne Full Tensor Gravity) surveys for two areas in southwestern and eastern Finland. In standard regional gravity surveys the average station interval was approximately 500 m.

Local gravity profiles were measured with a station spacing of 20 m. Local gravity surveys were conducted on regular grids of 20 m x 100 m. In addition to our own measurements, the data of the Finnish Geodetic Institute and the Fennoscandian 2.5 km x 2.5 km Bouguer anomaly grid were utilized. GTK contributed to and benefited from a substantial demand in Finland for commercial gravity work. Almost 60 % of the local measurements and more than 10% of the regional surveys were commercial or had external funding.

In the three-year period 2008-2010, the number of gravity stations measured by GTK was as follows:

1. Regional gravity measurements:
   11 473 stations
2. Airborne gravity gradiometry:
   1412 line-km
3. Local measurements:
   95 859 stations

At the end of 2010, the regional gravity database of the Geological Survey of Finland contained 274 500 gravity stations, which cover an area of 77 000 sq. km. An example of a regional gravity map is shown in Fig. 1.

GTK operates currently five Scintrex CG-5 gravimeters and one Worden gravimeter. In measuring the heights and coordinates of the regional gravity stations, GTK replaced GPS measurements based on a movable base station by a system utilizing the permanent Finnish network of GPS stations to provide VRS (Virtual Reference Station) positioning. In local surveys, heights of the gravity stations are currently measured by means of VRS GPS techniques or more commonly by means of chain levels (hydrostatic leveling).

A quality system for gravity measurements has been in use since 2002. Among other things, the calibration and behavior of the gravimeters are checked on the Masala-Vihti calibration line maintained by the Finnish Geodetic Institute.

Conversion of the old regional gravity data base to a new format was started. During the conversion the data is checked by new quality control algorithms and new terrain corrections are calculated for each gravity station using the 25 m x 25 m digital terrain model of the National Land Survey. The new data base contains coordinates in the old KKJ and the new EUREF-FIN systems and gravity anomalies calculated according to the old and new systems.

In bedrock research, targets included major fault and shear zones, stratigraphic cross-sections, greenstone belts, metamorphic zoning, mafic and granitic intrusions, sedimentary basins and meteorite impact craters. Important targets in exploration included ore-bearing mafic intrusions and bedrock structures in gold-prospecting areas. Mapping of mineralized geologic structures using geophysical potential field datasets has become an important part of exploration projects. All the known orogenic gold and IOCG deposits in the CLGB show intimate spatial correlation to shear zones of varying scale. Processed gravity worms (basically horizontal gradient of Bouguer anomaly) display striking spatial correlation with the known orogenic gold and IOCG deposits. In some cases the gold hosting shear zones are outlined by gravity worms either completely or partly whereas the presence of some major shear zones is indicated by truncation of worms at the location of the shear zone (Lahti et al. 2010). Gravity measurements provided important additional information to seismic reflection soundings such as obtained in HIRE project (e.g. Kukkonen et al. 2010). Moreover, results of a joint GPS, gravity and electromagnetic study of permafrost and continental ice in the Antarctica were published (Ruotoistenmäki and Lehtimäki, 2008).

The gravity method maintained its position in estimating overburden thickness mostly in conjunction with assessing and protecting groundwater resources and mapping contaminated soils (Elo, Pirttijärvi 2010; Valjus 2009). Altogether 1096 line-km of gravity profiles were measured and interpreted in 42 target areas resulting in 34 reports. The GPS-gravity measurements at a waste treatment center to obtain estimates for the subsidence rate and density changes of landfills have been repeated every year since 1999 for the Helsinki Region Environmental Services Authority (formerly the Helsinki Metropolitan Area Council).

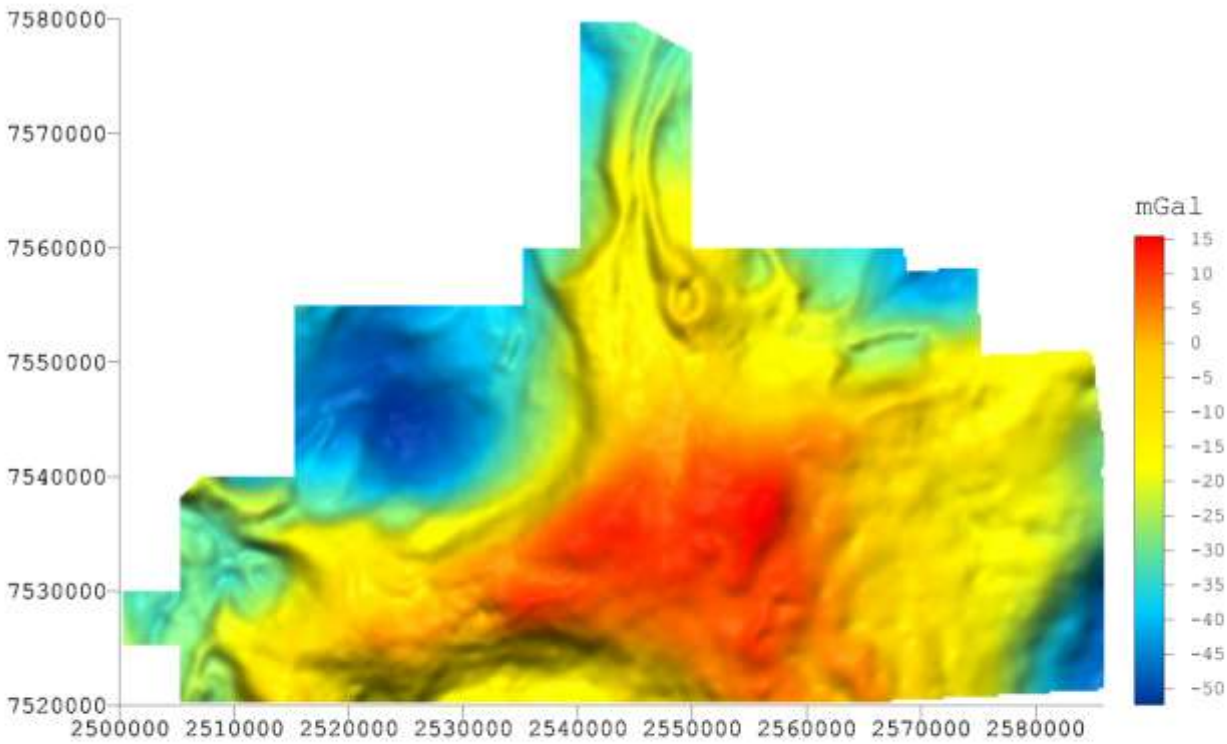

**Figure VIII-1**. A new regional Bouguer anomaly map of the northern part of the Kittilä greenstone belt ©Geological Survey of Finland.

As a major project, GTK ordered trial AirFTG (Airborne Full Tensor Gravity) surveys for two areas (Pori and Hammaslahti) in southwestern and eastern Finland. The purpose of the trial surveys was to assess the competitiveness of airborne gravity surveys in terms of prices, delivery times, resolution, accuracy and interpretability in comparison to regional ground gravity measurements with average station intervals of 400 meters to 1000 meters. Specifically, in Hammaslahti the aim was a multidisciplinary study of the geological structure, geological evolution, ore potential and thickness of eskers, and in Pori, the purpose was to estimate the thickness of sediments, to continue the previous interpretation of the bedrock structures into the marine environment and to provide a link between geophysical studies on land and marine seismic soundings. For the Pori area, altogether 198.15 km of lines were flown with a line separation of 1500 m and a tie line separation of 7500 m. For the Hammaslahti area, altogether 1370.50 km of lines were flown with a line separation of 1000 m for the whole area and of 500 m for two sub-areas, and with tie line separations of 5000 m and 2500 m.

Combining of airborne gravity gradient data with ground gravity data was studied in co-operation with the University of Oulu (Kallo, 2010; Pirttijärvi et al. 2009) using the data mentioned above. Combined with the irregularly sampled ground data, the more densely spaced airborne data will enhance the spatial information of the gravity field at the survey site. Airborne surveys can quickly cover large areas and do not have to deal with problems, such as swamps, rivers and lakes that hinder ground observations. By combining the airborne data with ground data, a derived Bouguer anomaly map can be made. Two primary methods were used to combine the data. The first method utilized Fourier transform and frequency domain filtering of the vertical Tzz component of the gravity tensor. The vertical component was first integrated and the resulting pseudo field was continued downward to ground level. Then several methods were tested to perform the actual data levelling. The main sources of error are the interpolation of the sparse ground data or residuals into regular grids and the downward continuation of the integrated Tz field by constant amount without taking the flight altitude and ground topography into consideration. The second method utilized equivalent two-layer models. An equivalent two-layer density model was first created by inverting together the irregularly sampled ground data and the interpolated airborne tensor data. Then the derived Bouguer data on a regular grid was computed by means of the equivalent layer model. Unlike in the filtering methods, original topography and flight altitude data were taken into account. The use of other tensor components was also possible. The best results were obtained by taking into account the diagonal elements of the gravity tensor. The biggest source of error is the interpolation of the topographic data to compute the derived Bouguer data. Because gradient data cannot portray the long wavelength variations of the gravity field, ground measurements are needed both inside and outside of the survey site to define the regional trend of the gravity field.

In the GeoSatakunta project (Elo and Pirttijärvi 2010), the Geological Survey of Finland has measured 2 832 new gravity stations in Satakunta and produced a set of gravity maps based on 5 234 observations of the Finnish Geodetic Institute, 30 279 observations of the Geological Survey of Finland and an airborne gravity survey of 198 line-km. New methods to process and model the overburden thickness and the effect of density variations on regional stress in the bedrock were developed. The thickness and contacts of overburden, sandstone, rapakivi granites and diabase sills were modeled. Sääksjärvi meteorite crater, intrusions, and bedrock blocks delineated by shear and fracture zones are also visible on the gravity anomaly maps. Interpreted from the gravity anomaly of about -30 mGal, the rapakivi granites extend to a depth of at least 8 km. They extend beneath the sandstone formation from Kokemäki to the coast of Pori and from the southwestern side of the sandstone to its northeastern side. Over the course of years, the deep structure of the rapakivi granites has been modeled in various ways. The fact is that no completely unique solution is possible, as different assumptions lead to different models. The common features of the various models should be emphasized. Based on gravity modeling, the average thickness of the sandstone formation is 1 300 ± 300 m in the Pori region and decreases towards the southeast. The outcropping or nearly outcropping diabase sills cover about 850 km2 of the map area and their total thickness is in places at least 400 m. The Sääksjärvi meteorite crater is 4 800 m in diameter and over 200 m deep. The crater is surrounded by fractured bedrock with a density clearly lower than that of the intact host rock. As compared to the theoretical crater models, only the lowermost part of the Sääksjärvi crater remains. Along the northern contact of the sandstone formation there is a bedrock valley filled with overburden, the thickness of which is commonly 50 to 100 m. The maximum effect of lateral density variations on the horizontal stress in the uppermost crust in Satakunta is estimated to be 8.5 MPa (maximum stress minus minimum stress). This is a substantial part of the estimated total regional stress in the bedrock. The standard difference of the geoid observed by the city of Pori and the geoid derived from the regional gravity measurements is ±3.8 cm. The computational geoid can be utilized as such or used as a control for other geoid determinations.

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# IX. Geodetic activities at the Department of Surveying, Geodesy Research Group, School of Engineering, Aalto University

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The Geodesy Research Group is currently an informal part of the Geomatics Research Group within the Department of Surveying, School of Engineering, Aalto University, http://maa.tkk.fi/en/gip/ (Formerly Helsinki University of Technology).

At Aalto University, research, teaching, and serving society are integrated. The Department of Surveying (http://maa.tkk.fi/en/) offers both a Bachelor's and a Master's level degree programme in Geomatics. Majors in the latter are Geodesy, Geoinformatics, and Photogrammetry and Remote Sensing. There is a special Master's programme aimed at foreign students offering Geoinformation Technology. Also post-graduate studies are on offer.

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