National Report of Sweden to the NKG General Assembly 2010

– geodetic activities in Sweden 2006-2010

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1. Geodetic activities at Lantmäteriet

LANTMÄTERIET

1.1 Introduction

At Lantmäteriet (the Swedish mapping, cadastral and land registration authority) the geodetic activities during 2006-2010 have been focused on:

- The Swedish network of permanent GNSS[1] stations (SWEPOS™), its expansion and the development of SWEPOS services such as a network RTK[2] service.
- The finalisation of the project RIX 95 with development of transformation parameters between national reference frames and local ones.
- The implementation of the Swedish national geodetic reference frame SWEREF 99, the Swedish ETRS 89[3] realisation.
- The implementation of the Swedish national height system RH 2000.
- The improvement of new national geoid models.
- Absolute gravity measurements on the Swedish absolute gravity sites and comparative measurements on Nordic sites.

1.2 Satellite positioning (GNSS)

1.2.1 GPS[4] campaigns

Lantmäteriet has participated in the NKG[5] 2008 GPS campaign (Jivall et al., 2010), which is a follow-up of the NKG 2003 GPS campaign. The campaign was carried out September 28–October 4 2008, aiming at developing a common reference frame in the Nordic-Arctic area and to improve and update the transformations from ITRF[6] to the national ETRS 89 realisations in the area. Lantmäteriet has co-ordinated the processing of the campaign.

1.2.2 NKG EPN[7] LAC[8]

Lantmäteriet operates the NKG EPN LAC in co-operation with Onsala Space

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[1] GNSS = Global Navigation Satellite Systems

[2] RTK = Real-Time Kinematic

[3] ETRS 89 = European Terrestrial Reference System 1989

[4] GPS = Global Positioning System

[5] NKG = Nordic Geodetic Commission (Nordiska Kommissionen för Geodesi)

[6] ITRF =International Terrestrial Reference Frame

[7] EPN = EUREF Permanent Network

[8] LAC = Local Analysis Centre

Observatory at Chalmers University of Technology. Totally 50 EPN stations concentrated to northern Europe are processed with the Bernese GPS software version 5.0, see Figure 1.1. This means that eight stations have been added to the NKG EPN LAC sub-network since the last NKG General Assembly four years ago. Both weekly and daily solutions based on final IGS[9] products are processed. Lantmäteriet has also represented NKG at the fifth, and sixth EUREF[10] LACs Workshops, which were held in 2006 and 2008. This is also the plan for the seventh workshop in autumn 2010.

The NKG EPN LAC will also contribute to the EPN reprocessing with solutions based on both the Bernese GPS Software and GAMIT. Bernese solutions for the pilot reprocessing of the year 2006 have been processed during 2009/2010.

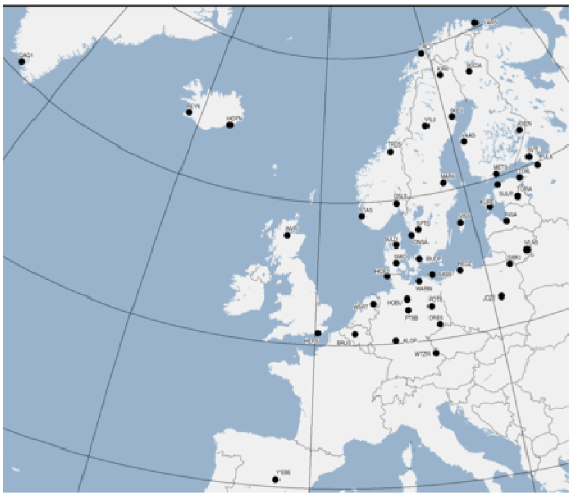

Figure 1.1: *The NKG EPN LAC sub-network of 50 permanent GNSS stations.*

1.2.3 EGNOS[11]

The EGNOS RIMS[12] that was inaugurated at Lantmäteriet in Gävle already during 2003 has been successfully supported by Lantmäteriet since then.

1.2.4 Swedish Radio Navigation Plan

The Swedish Radio Navigation Plan of 2009 is published by the Swedish Maritime Administration. Lantmäteriet has taking part in the working group within the Swedish Board of Radio Navigation that has produced the plan. Since early 2010, Lantmäteriet chairs the Swedish Board of Radio Navigation.

1.2.5 Nordic Positioning Service

Lantmäteriet has participated in the project Nordic Positioning Service. The major purpose was both to exchange data between the networks of permanent reference stations in Denmark, Norway and Sweden and to establish common positioning services. The project also implied exchange of knowledge in the fields of operation and applications of networks of permanent reference stations.

1.3 Network of permanent reference stations (SWEPOS)

SWEPOS™ is the Swedish network of permanent GNSS stations (Jämtnäs et al., 2010), see www.swepos.com.

The purposes of SWEPOS are to:

- Provide single- and dual-frequency data for relative GNSS measurements.

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[9] IGS = International GNSS Service

[10] EUREF = the IAG Reference Frame Subcommission for Europe
IAG = International Association of Geodesy

[11] EGNOS = European Geostationary Navigation Overlay System

[12] RIMS = Ranging and Integrity Monitoring Station

- Provide DGPS[13]/DGNSS[14] corrections and RTK data for distribution to real-time users.
- Act as the continuously monitored foundation of the national reference frame SWEREF 99.
- Provide data for geophysical research.
- Monitor the integrity of the GNSS systems.

During 2006, a sub-group of the NKG project Nordic Positioning Service developed a classification system of permanent GNSS stations (Engfeldt et al., 2006). The system includes four different classes; A, B, C and D, where class A is the class with the highest demands and the system was adopted by Lantmäteriet in 2007.

Today (September 2010) SWEPOS consists of totally 195 stations, 37 class A stations and 158 class B ones, see Figures 1.2 and 1.3.

Figure 1.2: *Överkalix is one of the SWEPOS stations belonging to class A.*

Figure 1.3: *Söderboda is a SWEPOS station with a roof-mounted GNSS antenna mainly established for network RTK purposes belonging to class B.*

This means that the total number of SWEPOS stations has increased with 90 stations since the last NKG General Assembly, see Figures 1.4 and 1.5.

The class A stations are built on bedrock and have redundant equipment for GNSS observations, communications, power supply, etc. They have also been connected by precise levelling to the national precise levelling network.

Class B stations are mainly established on top of buildings for network RTK purposes. They have the same instrumentation as class A stations (dual-frequency GPS/GLONASS receivers with antennas of Dorne Margolin design), but with somewhat less redundancy.

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[13] DGPS = Differential GPS

[14] DGNSS = Differential GNSS

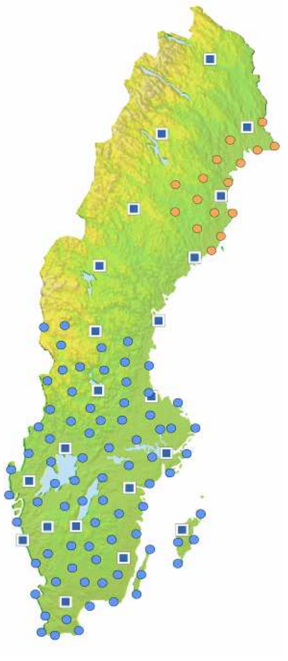

Figure 1.4: *The SWEPOS network by the time for the last NKG General Assembly in 2006. Orange dots are stations that were built after the meeting during the summer 2006.*

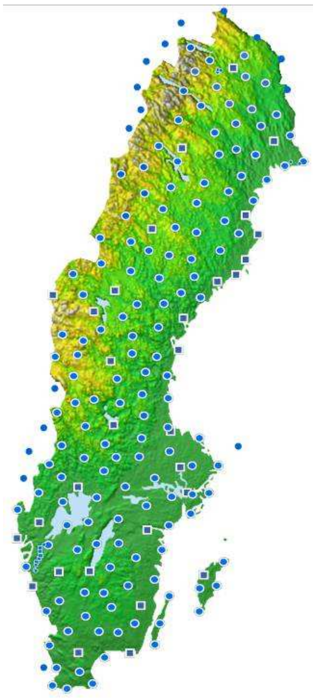

Figure 1.5: *The SWEPOS network in September 2010 with a number of bordering Norwegian, Danish and Finnish stations that are used in SWEPOS Network RTK Service. Squares are class A stations and dots are class B stations.*

An antenna calibration field was established in April 2007 on the roof of the headquarters of Lantmäteriet in Gävle, primarily for testing and calibration of the antennas used in SWEPOS. All new, re-built or problematic antennas in the SWEPOS network are tested on the test field.

Seven SWEPOS stations are included in EPN. These stations are Onsala, Mårtsbo, Visby, Borås, Skellefteå, Vilhelmina and Kiruna (ONSA, MAR6, VIS0, SPT0, SKE0, VIL0 and KIR0). Daily, hourly and real-time (EUREF-IP) data (1 second) are delivered for all stations, except for Vilhelmina, where just daily and hourly files are submitted.

Furthermore, Onsala, Mårtsbo, Visby, Borås and Kiruna are included in the IGS network and two stations (Skellefteå and Stockholm) are proposed to be included.

Sweden has also, according to the co-ordination within NKG, offered all seven Swedish EPN stations except Vilhelmina for ECGN[15]. GNSS data from SWEPOS stations are furthermore used in meteorological applications such as E-GVAP[16].

1.4 SWEPOS services

Both SWEPOS data for post-processing in RINEX[17] format and an automated processing service (available on www.swepos.com) have been available for a long time. Some developments have been done and during 2008 the processing service changed from

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[15] ECGN = European Combined Geodetic Network

[16] E-GVAP = EUMETNET EIG GNSS water vapour programme

[17] RINEX = Receiver Independent Exchange format

version 4.2 to version 5.0 of the Bernese GPS software.

The SWEPOS Network RTK Service was launched with regional coverage on January 1st 2004, using the VRS[18] technique. The service has been expanded with regional one-year-long establishment projects and it has during 2010 reached national coverage. Since data from permanent GNSS stations is exchanged between the Nordic countries, good coverage of the service in border areas and along the coasts has been obtained during the last years by the inclusion of 9 Norwegian SATREF stations, 7 Finnish Geotrim stations, 3 Danish Leica SmartNet stations and 1 Danish KMS[19] station.

The service has broadcasted RTK data for both GPS and GLONASS since April 1st 2006 and has today (September 2010) approximately 1480 subscriptions, which means approximately 1030 new users since the last NKG General Assembly.

During February 2008, a survey of the users of SWEPOS and its services was carried out by questionnaire. The survey had special focus on the network RTK service. Close to 400 answers were received from the 950 users that the service had at that point. Most of the users were very satisfied with the performance and “customer support” of the network RTK service and considered it to be worth its price.

There is an increasing use of RTK for machine guidance. To meet this, some densifications of the SWEPOS network have been done. In these areas are SWEPOS Network RTK Service used as a flexible and redundant service, tailor-made for large-scale infrastructure projects (Hedling et al., 2009). Further densifications are taking place during 2010 in the area around Stockholm, on the west-coast of Sweden and in the southern part of Sweden.

Existing guidelines concerning the use of the network RTK service have been improved during the last year (Odolinski, 2010). Several parameters have been handled as well as time correlation effects for points measured close to each other in time.

A project called “Close-RTK” has also been performed during the last year, with an effort to assess the quality of the present network RTK technique, as well as future development scenarios of space (GNSS) and ground (SWEPOS) infrastructure (Emardson et al., 2009 and Jämtnäs et al., 2010). The project was initiated by Lantmäteriet, SP Technical Research Institute of Sweden and Chalmers University of Technology. Parameters that were deeply studied were different sources of uncertainty in measurements (e.g. atmospheric and local effects), future satellite systems as Galileo and Compass and a general densification of the SWEPOS network (with 35 km between the stations).

SWEPOS also offers a single frequency Network DGNSS Service that was launched on April 1st 2006. Both this service and the network RTK service are using the network RTK/DGNSS software GPSNet from Trimble and GSM[20] or GPRS[21] (i.e. mobile Internet connection) as the main distribution channels.

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[18] VRS = Virtual Reference Station

[19] KMS = Kort & Matrikelstyrelsen

[20] GSM = Global System for Mobile communication

[21] GPRS = General Packet Radio Service

The Swedish DGPS service EPOS is using correction data from SWEPOS. EPOS is using the RDS[22] channel on the FM radio network for the distribution and in July 2007 the operator of this service changed from Cartesia Informationsteknik AB to Teracom AB.

1.5 The project RIX 95

The large project RIX 95, which involved GPS measurements on triangulation stations and selected local control points, was finalized in 2008. It started already in 1995 and the work was financed by a group of national agencies. The principal aim was to connect local coordinate systems to both the national reference frame SWEREF 99 and the old horizontal reference frame that SWEREF 99 has replaced, which is called RT 90. Another aim was to establish new points easily accessible for local GNSS measurements.

The outcome of the project is 9029 control points determined in SWEREF 99 and other existing national reference frames, see Figure 1.6. The outcome also consists of transformation relations between these reference frames as well as to local reference frames used by the municipalities. The transformations are based on so-called direct projection (Engberg & Lilje, 2006).

The measurements were to large extent made with standard equipment and with procedures for static observations. Around 300 of the points were however measured in a way that coordinates with very low uncertainty in SWEREF 99 could be obtained. These so-called SWEREF points are all marked in bedrock and the approximate distance between them are around 50 km. The observations lasted for 2x24 hours, with a new set up between the sessions. They were observed with antennas of Dorne Margolin T-type design and the Bernese GPS software was used for the processing.

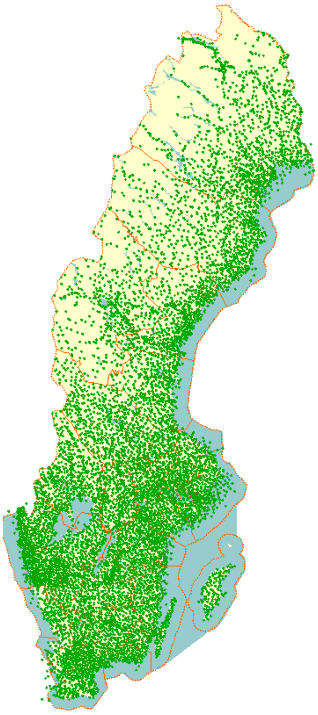

Figure 1.6: *The 9029 control points determined within the RIX 95 project that lasted 1995-2008.*

1.6 Implementation of SWEREF 99

By defining SWEREF 99 as an active reference frame we are exposed to rely on SWEPOS' positioning services like the network RTK service. All alterations of equipment and software as well as movements at the stations will in the end affect the coordinates. In order for the possibility to keep a check on all these alterations, so-called consolidation points have been introduced (Engberg et al., 2010). The approximately 300 SWEREF points

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[22] RDS = Radio Data System

from the RIX 95 project are used for this purpose, see Figure 1.7, and they will be remeasured in a yearly programme with 50 points each year.

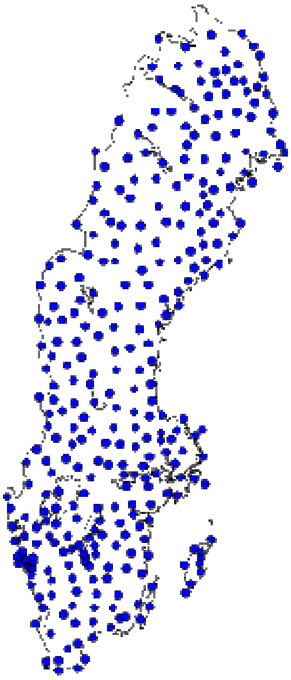

Figure 1.7: *The approximately 300 so-called SWEREF points from the RIX 95 project.*

A formal decision regarding map projections for SWEREF 99 for both national mapping and local surveying was taken in 2003. All the projections are of the Transverse Mercator type. In January 2007, Lantmäteriet replaced RT 90 with SWEREF 99 (and the national map projection called SWEREF 99 TM) in all databases and product lines. A new map sheet division and a new index system were also adopted.

The work regarding the implementation of SWEREF 99 among other authorities in Sweden, such as local ones, is in progress (Kempe et al., 2010). 87 % of the 290 Swedish municipalities have started the process to replace their old reference frames with SWEREF 99. The number of municipalities that have finalised the replacement has increased from 11 to 192 during the four past years.

In this process, a rectification of distorted geometries in the local reference frames is needed. The transformation parameters obtained from RIX 95 together with correction models based on new GNSS measurements are used for this purpose. The rectification is made by a so-called rubber sheeting algorithm and the result will be that all geographical data are positioned in a homogenous reference frame, the national SWEREF 99.

1.7 Implementation of RH 2000

The national height system RH 2000 is based on the third precise levelling of Sweden that lasted 1978-2003. The final adjustment was done in 2005. The land uplift model used called NKG2005LU was adopted as a Nordic model by NKG in 2006. The model is based on a combination and modification of the mathematical model of Olav Vestøl and the geophysical model of Lambeck, Smither and Ekman (Ågren & Svensson, 2007). The network consists of about 50,000 bench marks, representing roughly 50,000 km double run precise levelling measured by motorised levelling technique.

However, the third precise levelling continued on the island of Gotland in 2007. These observations were adjusted and connected to the mainland in RH 2000 in 2008 through a combination of tide gauge and GNSS/levelling observations, complemented by geoid/oceanographic models.

Since the beginning of the 1990's, a systematic inventory/updating of the network is continuously performed.

The work with implementing RH 2000 among other authorities in Sweden is in progress. 106 of the 290 Swedish municipalities have, in co-operation with Lantmäteriet, started the process of analysing their local networks, with the aim to replace the local height systems with RH 2000. So far, 33 municipalities have finalised the replacement for all activities, which is 29 more than by the time for the last NKG General Assembly four years ago.

1.8 Geoid models

The national Swedish geoid model, SWEN08_RH2000 was released in the beginning of 2009. It has been computed by adapting the Swedish gravimetric model KTH08 to the reference systems SWEREF 99 and RH 2000 by utilising a large number of geometrically determined geoid heights, computed as the difference between heights above the ellipsoid determined by GNSS and levelled normal heights above sea level. In this step, a correction has been applied for the postglacial land uplift and for differences in permanent tide systems. A smooth residual surface is used to model the GNSS/levelling residuals (residual interpolation).

The standard uncertainty of SWEN08_RH2000 has been estimated to 10-15 mm everywhere on the Swedish mainland with the exception of a small area in the north-west not covered by the third precise levelling, see Figure 1.8. The standard uncertainty is larger in the latter area and at sea, probably around 5-10 cm.

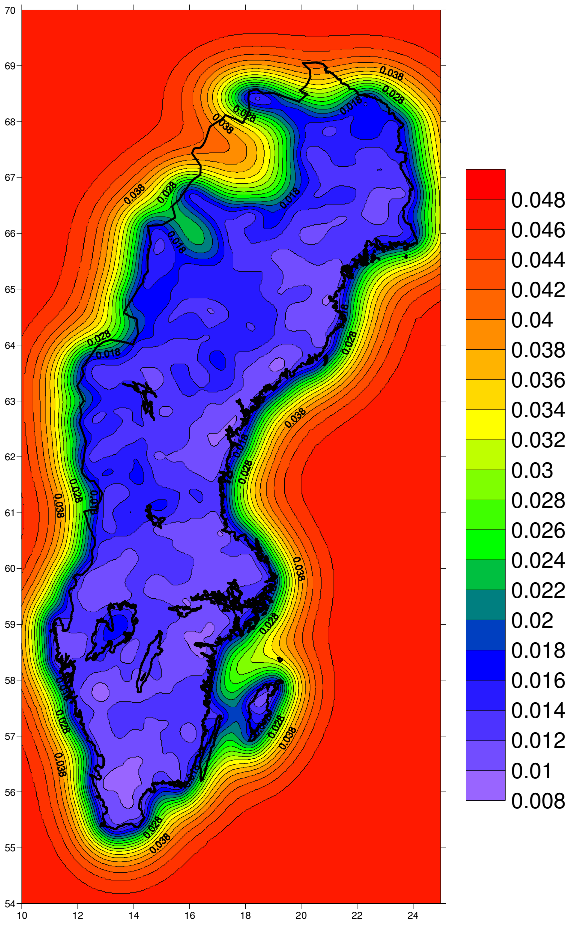

Figure 1.8: *Expected accuracy (standard uncertainty) for the geoid model SWEN08_RH2000 (metre).*

The underlying gravimetric model, KTH08, has been computed by the technique called LSMSA[23]. This work has been made in co-operation with Professor Sjöberg and his group at KTH[24] in Stockholm (Ågren et al., 2009).

Another geoid related activity during the last four years has been the evaluation of EGM 2008[25] (Ågren, 2009).

Presently Lantmäteriet investigates what is required of the national gravity system and gravity data to be able to compute a more accurate geoid model

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[23] LSMSA = Least Squares Modification of Stokes Formula with Additive Corrections

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

[25] EGM2008 = Earth Gravitational Model 2008

in the future (with standard uncertainty of the order 5 mm). Two preliminary conclusions from this ongoing project (not yet published) are that a new gravity system is needed and that 5 km resolution is sufficient for the detail gravity. Besides, a significant amount of new observations are required and the old data need to be checked and updated in various ways.

1.9 Gravimetry

The number of Swedish sites where absolute gravity observations have been carried out has increased from 11 to 14 sites since the last NKG General Assembly, see Figure 1.10.

In the autumn of 2006, Lantmäteriet purchased a new absolute gravimeter (Micro-g Lacoste FG 5 - 233), see Figure 1.9. The objective behind this investment is to ensure and strengthen the observing capability for long term monitoring of the changes in the gravity field due to the Fennoscandian GIA[26].

Figure 1.9: *The new FG5 absolute gravimeter and the observer team during the on-site training course. Photo: Mikael Lilje.*

Lantmäteriet has since 2007 made absolute observations with the new instrument on 12 of the Swedish sites, but also on 1 Danish site, 1 Finnish site, 2 Norwegian sites, 3 Serbian sites and at two inter-comparisons (one with 19 other gravimeters in Luxembourg and one with 22 other gravimeters in Paris).

All Swedish sites are co-located with permanent reference stations for GNSS in the SWEPOS network (except for Göteborg which is no longer in use). Onsala is also co-located with VLBI[27]. Skellefteå, Smögen, and Visby are co-located with tide gauges.

The absolute gravity observations are co-ordinated within NKG, and observations have also been performed by several groups (BKG[28], IfE[29], UMB[30] and FGI[31]) together with Lantmäteriet. This arrangement has made it possible to observe 7 of the sites every year since 2003 (marked with green background circles in Figure 1.10).

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[26] GIA = Glacial Isostatic Adjustment

[27] VLBI= Very Long Baseline Interferometry

[28] BKG = Bundesamt für Kartographie und Geodäsie, Germany

[29] IfE = Institut für Erdmessung, Universität Hannover, Germany

[30] UMB = Universitetet for Miljø og Biovitenskap, Norway

[31] FGI = Finnish Geodetic Institute, Finland

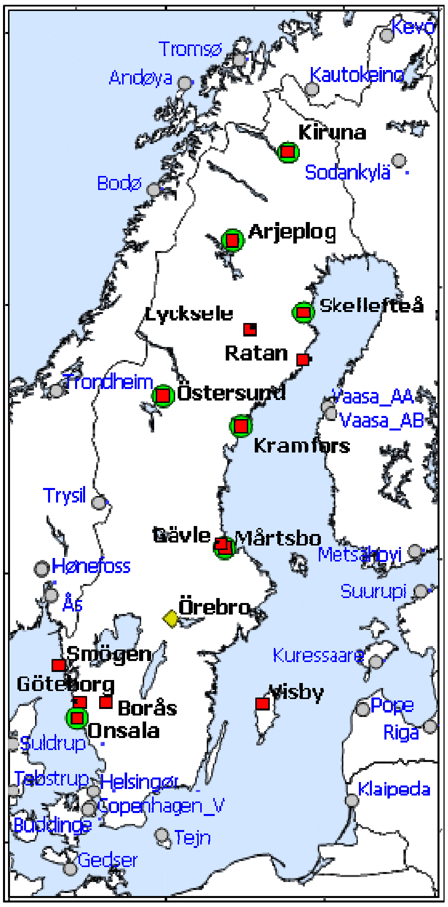

Figure 1.10: *Absolute gravity sites in Sweden (red squares), planned new site (yellow diamond) and sites in neighbouring countries (grey circles). Sites observed every year since 2003 have a green circle as background to the red square.*

At Onsala Space Observatory, a superconducting gravimeter was installed during the summer 2009, see Section 3.3.

1.10 Geodynamics

The main purpose of the repeated absolute gravity observations is to support the understanding of the physical mechanisms behind the Fennoscandian GIA process, where the relation between gravity change and geometric deformation is a primary parameter.

Research regarding the 3D geometric deformation is foremost done within the BIFROST effort. Reprocessing of all observations from continuously operating GPS stations since autumn 1993 up to autumn 2006 has been done (Lidberg, 2007, Lidberg et al., 2007 and Lidberg et al., 2010). The results agree with an updated geophysical, meaningful GIA model at the sub-mm/yr level.

A coordinate transformation scheme has been developed for high-precision survey applications using GNSS relative permanent reference stations. Internal deformations are accounted for in the scheme. The used deformation model (NKG_RF03vel), which is based on the results from BIFROST and on the land uplift model NKG2005LU, is implemented in the automated processing service offered by SWEPOS, see Section 1.4.

1.11 Further activities

1.11.1 Diploma works

During the period 2006-2010 totally 11 diploma works have been performed at Lantmäteriet by students from KTH, the University of Gävle and Högskolan Väst in Trollhättan. 8 of the diploma works have mainly been focused on GNSS and to large extend the SWEPOS services. 3 of them have mainly been focused on reference systems, partly with the objective to support the implementation of new reference systems.

1.11.2 Doctoral dissertations

Two persons from Lantmäteriet have performed doctoral studies at Onsala Space Observatory. One study dealt with geodetic reference frames in presence of crustal deformations

(Lidberg, 2007). The other one, that presently is going on, deals with the understanding and modelling of the dynamics of the Earth and it's gravity field in terms of response to surface loads. It has special emphasis on GIA and the Fennoscandian land uplift area (Olsson et al., 2009).

1.11.3 Arranged workshops and seminars

The Struve Geodetic Arc bi-annually International Conference about this world heritage was arranged in Haparanda and Pajala in August 2006.

Figure 1.11: *An opening ceremony for the Swedish Struve world heritage points was held in 2006 at the point Jupukka. The mayor of Pajala municipality, Bengt Niska and the president of the Swedish Royal Academy of Sciences, Kerstin Fredga, are standing by the pole. Photo: Tõnu Viik.*

The NKG workshop "Capabilities and Development of Network-RTK in the future" was organised in Gävle in April 2009 with approximately 50 participants.

A European meeting of the International Subcommittee of CGSIC[32] was held in Stockholm in October 2009. It was arranged in co-operation with AJ Geomatics and approximately 60 persons attended the meeting.

A meeting in RTCM SC-104[33] took place in Gävle in February 2010.

The yearly EUREF symposium was arranged in Gävle June 2-5 2010 in co-operation with KTH and Onsala Space Observatory. It gathered 129 participants from 29 countries.

For Swedish GNSS users, seminars were arranged in Gävle in March 2007 and October 2009. The aim of these bi-annually seminars is to highlight the development of GNSS techniques, applications of GNSS and experiences from the use of GNSS. Many locally arranged seminars have also had key speakers from Lantmäteriet, who have informed about things like SWEPOS, SWEPOS services and the implementation of SWEREF 99 and RH 2000.

1.11.4 Web-page

The Lantmäteriet web-page (www.lantmateriet.se/geodesi) has extensive geodetic information. Here also transformation parameters and geoid models are easily and freely accessible.

1.11.5 Digital geodetic archive

The geodetic archive with descriptions of points and their coordinates and

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[32] CGSIC = Civil GPS Service Interface Committee

[33] RTCM SC-104 = Radio Technical Commission for Maritime Services Special Committee No. 104

heights etc. has been made digital. The web-page was opened for both internal and external users in October 2007. Today (September 2010), 109 external users are registered and they pay a small yearly fee.

1.11.6 Plan for geodetic activities

GEODESI 90 and Geodesi 2000 are previously published 10 year long plans for geodetic activities in Sweden. A strategic plan for the years 2011-2020 called Geodesi 2010 is under construction and the plan is to have it published before the end of 2010.

1.11.7 National elevation model

Lantmäteriet are responsible for the production of a new Swedish national elevation model. The final decision for this was taken by the Swedish government in December 2008. Airborne laser scanning is mainly used and the production started in July 2009. The scanning will continue to 2012 and all parts of the production will be finalised in 2015.

1.11.8 Participation in projects overseas

Lantmäteriet are involved (partly through the state-owned company Swedesurvey) in many projects abroad. Many projects have a geodetic part and typical components are the update of reference frames and the implementation of modern surveying techniques based on GNSS.

Countries where geodetic personnel have had assignments over the last four years are Albania, Armenia, Belarus, Bhutan, Botswana, China, Georgia, Indonesia, Jamaica, Kenya, Kyrgyzstan Macedonia, Mongolia, Serbia, Syria and Tajikistan.

Figure 1.12: *Personnel from Lantmäteriet introducing RTK surveying for DSLR*[34] *in Bhutan. Photo: Tenzin Namgay.*

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

2. Geodetic activities at KTH, the Royal Institute of Technology

2.1 Introduction

The Division of Geodesy at the Royal Institute of Technology (KTH) in Stockholm offers graduate and postgraduate education as well as performs research in geodesy and surveying. Below we summarize these activities for the period 2006-2010.

2.2 Graduate programme

Geodesy courses have been taught as a part of the Geomatics Engineering specialization of the MSc programme “Samhällsbyggnad” (Built Environment). The number of students attending these courses varies greatly from 3 to about 25. The following courses have been given during the period 2006-2010:

- Geodetic surveying
- Analysis of measurements (Theory of errors)
- Map projections
- Reference systems
- Satellite positioning with GPS
- Physical geodesy
- Integrated navigation
- Engineering surveying

Since autumn 2007 there is also a 2-year international master programme “Geodesy and Geoinformatics” with several courses co-ordinated with the previous programme. About 20 students from Europe, Asia, Africa and Latin America, are recruited each year. During the report period, staff members of the Division of Geodesy have participated in 4 European Union Tempus projects which lead to the establishment of 4 new university programmes in geodesy and GIS[35] for Modolva, Kyrgyzstan, Kazakhstan and Tajikistan, respectively.

2.3 Postgraduate programme

Since 2006 five postgraduate students have successfully defended their Ph.D. theses in the fields of displacement monitoring using GPS (Andersson, 2008), laser scanning (Reshetyuk, 2009), geoid determination (Kiamehr, 2006 and Ulotu, 2009) and satellite gradiometry (Eshagh, 2009). For the time being there are six active postgraduate students.

2.4 Physical geodesy

This project is a continuation of a long-term research programme in physical geodesy at the Royal Institute of Technology (KTH) with the overall scientific objective of improving the theory and corrections needed in order to compute the geoid to 1 cm accuracy.

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[35] GIS = Geographical Information Systems

Figure 2.1: *At the EUREF symposium in Gävle June 2-5 2010, which was arranged in co-operation between Lantmäteriet, KTH and Onsala Space Observatory, a presentation was held about a rigorous formula for the geoid-to-quasigeoid separation. The session was chaired by Markku Poutanen of FGI. Photo: Örjan Zackrisson.*

The KTH geoid computation technique, called LSMSA[36], is unique in the senses that it uses 1) least squares modification of Stokes formula and 2) adds all corrections for topography, atmosphere and ellipsoidal effects separately as combined corrections.

Most of this development was completed during 2006-2010, and the method has proved to be the best in tests, or at least not worse than any other method, among these tests an international comparison of gravimetric geoid software packages vs. GPS-levelling geoid models. For references, see Ågren et al. (2008) and (2009), and Ulotu (2009).

Sjöberg and Eshagh (2009) presented a new method for geoid determination from airborne gravity data. Other studies dealt with a technique to determine the geoid and orthometric heights from satellite positioning and geopotential numbers (Sjöberg 2006a) and refinement of the conversion from normal to orthometric height (Sjöberg 2006b). Also, Sjöberg (2009a) presented a new method to determine Moho depth by using Vening Meinesz-Moritz hypothesis of a global isostatic compensation of the topography with a spherical approximation of sea level.

When computing the precise geoid by standard or modified Stokes formula (e.g. the RCR-method), the correction for the topographic masses is a considerable workload. This job is very significantly reduced in the LSMSA method, where the combined topographic correction is reduced to that of the spherical Bouguer correction, while the additional terrain correction is eliminated. See Sjöberg (2007a), (2008a), (2009a).

The KTH-method, based on LSMSA, has been applied in 3 Master’s thesis projects to compute geoid models for Greece (Daras et al. 2008), Sudan and Kazakhstan, respectively.

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[36] LSMSA = Least Squares Modification of Stokes Formula with Additive Corrections

3. Geodetic activities at Chalmers University of Technology and Onsala Space Observatory

3.1 Introduction

Onsala Space Observatory is the Swedish national facility for radio astronomy. It is hosted by the Department of Earth and Space Sciences at Chalmers University of Technology, where the Space Geodesy and Geodynamics research group are focused on three techniques for geodetic, geophysical and other earth oriented applications:

- Geodetic VLBI
- Gravimetry
- GNSS

Co-location work between the different techniques is also performed.

3.2 Geodetic VLBI

The Space Geodesy and Geodynamics research group has actively participated in the observing programme of IVS[37]. On average, about 25 geodetic VLBI sessions were performed every year, using the Onsala 20 m radio telescope and VLBI equipment. The observed sessions are part of IVS' earth rotation programme, terrestrial reference programme, celestial reference system programme, and the European geodetic VLBI series. Additionally, we participated in the 14 days long continuous campaign CONT08 that produced highest quality state-of-the-art VLBI results. Data analysis of the CONT08 session revealed that the Onsala station is one of the two stations with best performance out of the 11 participating stations worldwide. The CONT08 data are also an important reference data set for the VLBI2010 simulation work.

We analyse Geodetic VLBI observations to derive accurate information about Earth orientation and rotation on various time scales. A wavelet decomposition of the length-of-day (lod) derived from a global geodetic VLBI data set is presented in Figure 3.1. It reveals signatures of global-scale mass redistribution processes on various time scales. Among them is the so-called El-Nino phenomenon.

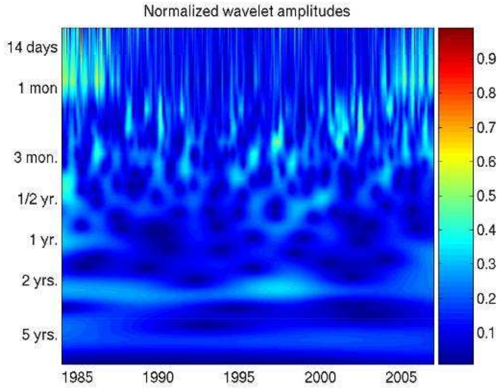

Figure 3.1: *Wavelet analysis of length-of-day (lod) results derived from a global geodetic VLBI data set. Variations on different time scales are clearly visible, related to global-scale mass redistribution processes.*

In 2007 we started together with colleagues in Finland and Japan the Fennoscandian-Japanese ultra-rapid

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[37] IVS= International VLBI Service for Geodesy and Astrometry

dUT1-project. This project aims at producing low latency earth rotation results using e-VLBI. Observations are preformed on extended east-west oriented baselines between Fennoscandia and Japan. The observed data from the Fennoscandian radio telescopes are transferred in real-time to a Japanese correlator centre and correlated in near real-time together with the corresponding observational data of the Japanese radio telescopes, and successively analyzed in near real-time to produce low latency results on UT1. The current low-latency world record was achieved in 2008 with the determination of final UT1 results within 4 minutes after the end of a one hour long observation session. The agreement with the final IERS[38] 05 EOPC04 values proved to be on the order of 30 microseconds. This is on the same level as the standard IERS rapid solutions, but with a much lower latency. Since 2009 the project is extended to regular 24 hours IVS sessions.

During 2006 to 2010 we contributed actively to the development of VLBI2010, the next generation geodetic VLBI system, with simulations of atmospheric propagation delays and an evaluation of the importance of atmospheric turbulence for geodetic VLBI. The simulations are based on turbulence models and aim at producing realistic propagation delays. Atmospheric turbulence is described by turbulence parameters Cn that can be derived e.g. from high-resolution radiosonde profiles. Our work shows that atmospheric turbulence is an important limiting factor for geodetic VLBI today and also for the future VLBI2010 system.

Another approach to address the issue of atmospheric propagation delays in geodetic VLBI data analysis is the use of external information to model these effects. We work on the use of data from Numerical Weather Models (NWM), e.g. the data provided by the European Centre for Medium-range Weather Forecast (ECMWF), to calculate line-of-sight corrections for geodetic VLBI data by ray-tracing. The aim is to use these corrections as improved a priori data for the data analysis, or as a way to calibrate the VLBI data. Our focus is on the European VLBI data set.

In 2009 we started a collaboration with the radio telescopes in Medicina and Noto, both Italy, and colleagues at Metsähovi (Finland) and JIVE (The Netherlands) to develop a strategy to observe GNSS-satelltie signals with VLBI. The idea is to do VLBI observations with GNSS-signals and to relate these to normal geodetic observations of natural radio sources. This could be a way to connect the satellite orbits to the celestial reference frame and thus a new tie of GNSS and VLBI. Several tests were performed and first attempts of data correlation and analysis are promising.

In 2009 we started a project together with the SP Technical Research Institute of Sweden to evaluate the potential of geodetic VLBI for time and frequency transfer. Geodetic collocation sites with equipment for VLBI and GNSS that are connected to common time and frequency distribution by H-masers are perfect candidates for time and frequency transfer experiments. We used the CONT08 data set for a

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[38] IERS= International Earth Rotation and Reference Systems Service

comparison and evaluation of frequency transfer with VLBI and GNSS. Our results show that geodetic VLBI can reach frequency transfer stability of 1e-15 during one day, and that this is in good agreement with GNSS-based techniques.

We use the global geodetic VLBI data set to derive long time series of tropospheric zenith wet delay (ZWD) and atmospheric gradient values. For Onsala, these time series cover more than 25 years. The ZWD can be converted into information on the integrated water vapour content (IPWV) and compared to independently derived IPWV results from a ground based microwave radiometer operated at Onsala and radiosonde observations from the Landvetter-Gothenburg airport. Figure 3.2 shows the corresponding time series.

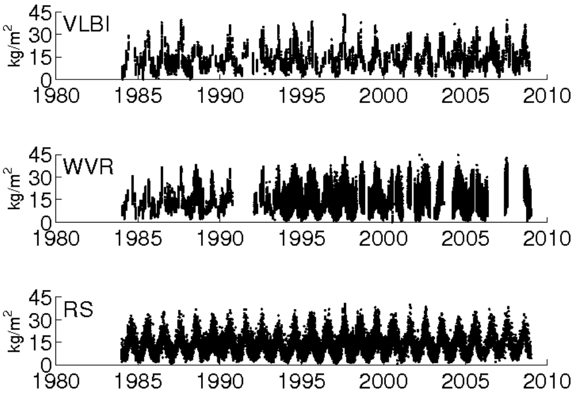

Figure 3.2: *Time series of integrated precipitable water vapor (IPWV) as determined from geodetic VLBI data observed at Onsala (VLBI, top) microwave radiometry at Onsala (WVR, middle) and radiosondes at Gothenburg-Landvetter (RS, bottom).*

The IPWV data derived from the individual techniques show high correlation with correlation coefficients of 0.95 and better. All three techniques show positive trends for the IPWV on the order of 0.4 to 0.6 kg/m2 per decade. However, the agreement is not perfect. A major problem in the comparison is the different sampling of the three data sets and the individual data gaps. Synchronization of the data sets results in small biases on the order of 1 kg/m2 and root-mean-square (RMS) differences of less than 2 kg/m2, but does not improve the agreement of the trends.

3.3 Super-conducting gravimetry

On June 10 2009, a super-conducting gravimeter (SCG, series number GWR-054) was taken into operation at the Onsala Space Observatory. The main use of the new facility is providing a calibrated gravity station for visiting groups within absolute gravity projects aiming e.g. at determining gravity changes in the Nordic countries in connection with GIA. The new gravimeter station provides us with the "third pillar" of geodesy, i.e. gravity and geopotential measurement, complementing our contributions the other two pillars, earth rotation and earth deformation. This development has now raised Onsala to the status of a Fundamental Geodetic Station, a core stations for the maintenance of the International Reference System. Figure 3.3. presents the gravimeter record for slightly more than one year. Several external research groups with absolute gravimeters have been visiting Onsala since mid 2009 to do parallel measurements with the new instrument.

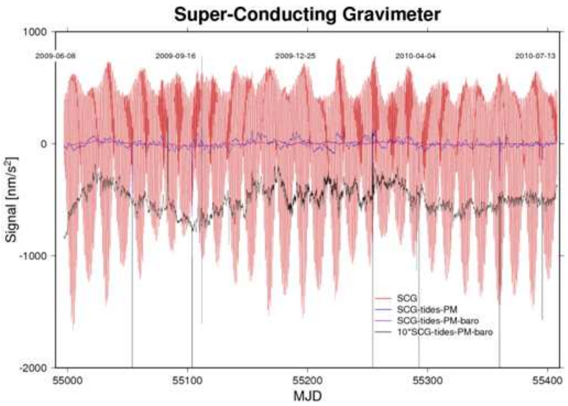

Figure 3.3: *Gravity signal recorded with the super-conducting gravimeter at Onsala Space Observatory.*

3.4 GNSS

3.4.1 Measuring sea surface height using GNSS signals

During 2008 we started a project to measure local sea level and its variation using GNSS signals. The measurements are done using a dual GNSS antenna assembly, that we call a GNSS based tide gauge, at the coast at the Onsala Space Observatory, see Figure 3.4. One antenna is directed upward, receiving the direct GNSS signals, and measuring the land surface height, whereas the other antenna is directed downward, receiving the GNSS signals reflected from the sea surface, and measuring the sea surface height.

The analysis of phase measurements performed with the corresponding GNSS receivers allows to estimate the local sea surface height and its variation. Results from hourly solutions of the local sea level at Onsala were compared with data from two stilling well gauges, operated by SMHI[39] at Ringhals and Göteborg about 18 km south and 33 km north of Onsala, respectively (Löfgren et al., 2010). The results show that the pair wise root-mean-square agreement between the three independent time series was better than 4 cm, indicating that the GNSS-based tide gauge gives valuable results for sea level monitoring.

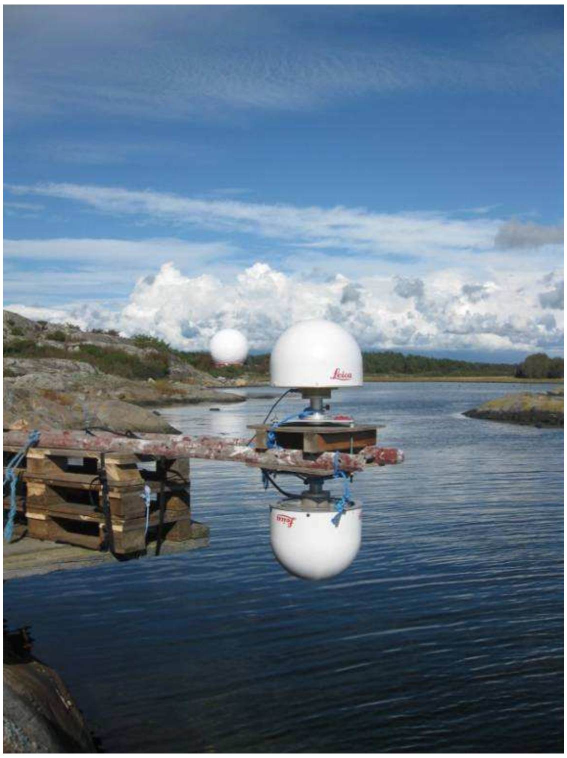

Figure 3.4: *GNSS-based tide-gauge at the Onsala Space Observatory.*

3.4.2 Using GNSS signals to measure the long term change of the Earth's atmospheric water vapour

Water vapour is a key element in our climate system. It takes part in the hydrological cycle by transporting water in the atmosphere and redistributing energy through evaporation and condensation and it affects the precipitation and soil moisture. Water vapour is also the most important green-house gas, absorbing and trapping radiations emitted from the Earth's surface. Therefore, Knowledge of the concentration and long-term changes of water vapour in the Earth's atmosphere is of crucial

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[39] SMHI = Swedish Meteorological and Hydrological Institute

importance for the operational weather and climate forecasting. However, due to it is variable both spatially and temporally, measuring the content of the water vapour, especially for long time series is difficult. Based on the timing of radio waves propagating through the atmosphere, GNSS can be used to determine the amount of atmospheric water vapor above receivers on the ground. Along with densification and extension of permanent GNSS station networks globally, using GNSS measurement to estimate atmospheric water vapour content is a promising application.

Motivated by the purpose to validate and improve climate models, which normally are used for forecasting and also to assess our future climate, independent measurements of the content of the Earth's atmospheric water vapour from continuously operating GNSS networks are used. In the project, longer time series observations (some up to 15 years) from more than 100 GNSS sites (most of them in Europe, and some global) are analyzed, see Figure 3.5.

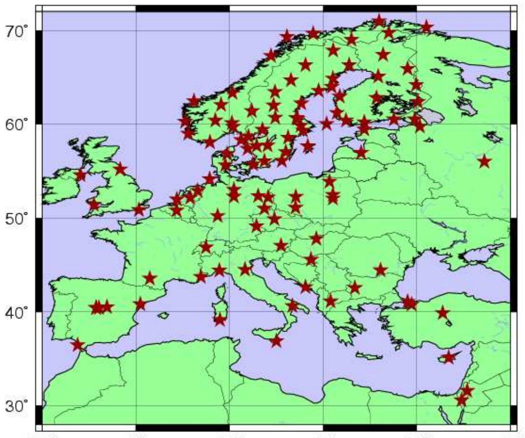

Figure 3.5: *The distribution of the GNSS stations used in the project with independent measurements of the content of the Earth's atmospheric water vapour.*

Systematic effects will be studied in order to obtain realistic trends, with small uncertainties. The GNSS estimates are compared to the water vapour content derived from two climate models. The results are not only interesting for the climate applications, but also can be used to improve the performance of GNSS techniques.

3.4.3 Investigations on the electromagnetic environment of the GNSS ground-based antennas

After decades of continuous development, data from GNSS have been used successfully in many applications. For example, continuously operating GPS stations have significant advantages for determining the Earth's atmospheric water vapour content. The formal uncertainty is in the order of 0.5 kg/m2 and Root-Mean-Square (RMS) difference seen in comparisons to other instruments, such as radiosondes and microwave radiometers. Based on the highly precise orbit information and consistent Earth orientation parameters, the accuracy of horizontal position estimates from the GPS data are at the millimetre level. However, to get the same accuracy in the vertical component of the coordinate estimates from GNSS, the impact of the electromagnetic environment of the GNSS antennas, i.e. scattering and multipath reflection, should be investigated and mitigated. Therefore the influence on the measurements from attaching anti-reflection material, i.e. microwave absorbers to the GNSS antenna is of great interest to study. Additionally, many antennas of geodetic stations are protected by radomes from extreme weather conditions. The effects from the installation of radomes are also important to know.

At the Onsala Space Observatory, an experimental pillar was constructed for flexible mounting of GNSS antennas for different scientific studies. A 3-dimensional positioning adjustment was mounted below the antenna. Hence the antenna can be moved in different directions with respect to the radome and the pillar. Meanwhile an arrangement was implemented to be able to move the radome up or down relative to the pillar. To investigate the effects of the different electromagnetic environment, the observations from the experimental pillar were obtained with different geometries of the absorber and the radome, i.e. with or without radome, and with or without absorber below or around the antenna, see Figure 3.6. The results show that the use of the microwave absorber decreases multipath effects up to 80 % both on the estimates of the vertical component of the coordinate and the atmospheric water vapour content. The implementation of the hemispheric radome gives neglect effects.

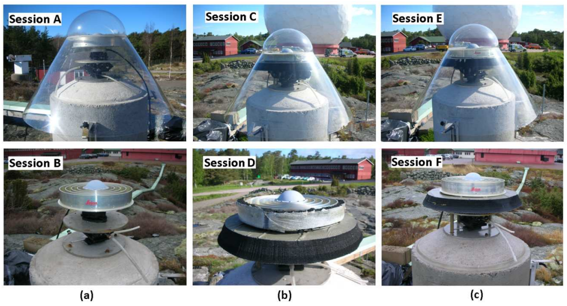

Figure 3.6: *Photographs of the experimental station with (top) and without (bottom) the radome having, (a) no absorber, (b) the absorber attached both under and around the antenna, and (c) the absorber attached under the antenna ground plane only.*

3.5 Co-location work

In 2008 we performed a repeated local tie measurement at the Onsala Space Observatory. A laser tracker was used to determine the reference point of the 20 m radio telescope and the connection to the IGS monument. The outcome of this project confirmed in general the 2002 local tie work. However, the new measurements provided a local tie with full covariance information.

In a master's thesis project started in 2009 we did a survey of the local gravity field at the Onsala Space Obseratory. A Lacoste-Romberg relative gravimeter was used and a large number of survey points at the observatory were observed. Also the gravity tie between the old gravity hut and the new gravity hut was determined.

In 2009 we performed the project 'Cold Magics' at the Ny-Ålesund Geodetic Observatory. The aim of this project was to achieve continuous monitoring of the local tie and local survey network at a co-location site. A single robotic total station was used for this project and differential motion larger than 1 was detected mm between observation targets attached to the VLBI and GNSS monument.

In 2010 we set up a similar project at Onsala, however with the aim to monitor different type of GNNS monuments and the effect of environmental stress on these monuments. This time we applied two robotic total stations.

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[40] GGEO = Gravity, Geoid & Earth Observation

[41] FIG = Fédération Internationale des Géomètres (International Federation of Surveyors)

[42] IAIN = International Association of Institutes of Navigation

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[43] IGFS = International Gravity Field Service of the IAG

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[44] AGU = American Geophysical Union

[45] IGFS = International Gravity Field Service of the IAG

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[46] FIG = Fédération Internationale des Géomètres (International Federation of Surveyors)

[47] IAG = International Association of Geodesy

[48] EUREF = IAG Reference Frame Subcommission for Europe

[49] NKG = Nordiska Kommissionen för Geodesi (Nordic Geodetic Commission)

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[50] GGEO = Gravity, Geoid & Earth Observation

[51] IAIN = International Association of Institutes of Navigation

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[52] EUGIN = European Group of Institutes of Navigation

[53] ENC = European Navigation Conference

[54] DVW = Deutscher Verein für Vermessungswesen

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[55] NGOS = Nordic Geodetic Observing System

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[56] ION = The Institute of Navigation

[57] ITM = International Technical Meeting

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[58] IGS = International GNSS Service

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[59] EGU = European Geosciences Union

[60] IUGG = International Union of Geodesy and Geophysics

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

[62] RNN = Radionavigeringsnämnden

[63] SLF = Sveriges Lantmätareförening

[64] KIF = Kartteknisk Intresseförening

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