National Report of Sweden to the EUREF 2017 Symposium

– geodetic activities at Lantmäteriet

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1 Introduction

At Lantmäteriet (the Swedish mapping, cadastral and land registration authority) the activities in the fields of geodetic reference frames and positioning are focused on:

- The operation, expansion and services of SWEPOS™, the Swedish national network of permanent reference stations for GNSS[1].
- Contributions of SWEPOS data to international initiatives as EPN[2], IGS[3] and MGEX[4] and international analyses of GNSS data.
- The implementation of the Swedish national reference frame SWEREF 99 and the national height system RH 2000 (ETRS[5]89 and EVRS[6] realizations respectively).
- The sustainability of the Swedish reference frames.
- Improvements of Swedish geoid models and renovation of the gravity network.

The geodetic work within Lantmäteriet is presently based on a 10-year strategic plan for the years 2011–2020 called *Geodesy 2010* released in 2011 and updated in 2015 (Lantmäteriet, 2011, 2015), and some of the activities are performed within the framework of NKG[7]. A new strategic plan is planned to be released in the end of 2017, initiated by the release of a new national Geodata Strategy in 2016.

2 Contributions from Lantmäteriet to EPN

The number of SWEPOS stations included in EPN is 27. Seven stations have been included since the very beginning of EPN and are all part of the 21 original SWEPOS stations. These stations are Onsala, Mårtsbo, Visby, Borås, Skellefteå, Vilhelmina and Kiruna (ONSA, MAR6, VIS0, SPT0, SKE0, VIL0 and KIR0). The other 20 stations also originate from the 21 original SWEPOS stations, but from an additional monument equipped with individually calibrated antennas/radomes (see chapter 4). Daily and hourly data are delivered for all stations. Real-time (EUREF-IP) data (1 Hz) are delivered from ten stations. There is one new monument for the last original SWEPOS station that is expected to be included in EPN later on.

Lantmäteriet operates the NKG EPN AC[8] in co-operation with Onsala Space Observatory at Chalmers University of Technology. The NKG AC contributes with week-

[1] GNSS = Global Navigation Satellite Systems
[2] EPN = EUREF Permanent Network
[3] IGS = International GNSS Service
[4] MGEX = Multi-GNSS Experiment
[5] ETRS = European Terrestrial Reference System
[6] EVRS = European Vertical Reference System
[7] NKG = Nordic Geodetic Commission (Nordiska Kommissionen för Geodesi)
[8] AC = Local Analysis Centre

ly and daily solutions based on final CODE[9] products, using the Bernese GNSS Software. The EPN sub-network processed by the NKG AC consists of 88 reference stations (April 2017) concentrated to northern Europe. Since the previous EUREF Symposium, 15 stations have been added and one station was removed due to its closing down.

3 EPN related GNSS Analysis

The NKG GNSS analysis centre project is chaired by Lantmäteriet (Jivall et al., 2014). The project aims at a dense and consistent velocity field in the Nordic and Baltic area. Consistent and combined solutions are produced based on national processing using the Bernese GNSS Software version 5.2, following the EPN Analysis guidelines. The project was declared fully operational in April 2017. A reprocessing, covering the years 1997–2016 with a processing setup consistent with EPN Repro2, of the full NKG network including all Nordic and Baltic countries is well underway.

Lantmäteriet has taken over the GNSS data processing for E-GVAP[10] (egvap.dmi.dk) from Chalmers University of Technology. The work started in June 2015 by moving and modifying the GIPSY/OASIS II v.6.2 solution (NGA2) and preparing a new solution (NGA1) using the Bernese GNSS Software v.5.2. Since June 2016 Lantmäteriet started transferring the estimated zenith total delay (ZTD) in near real-time to SMHI[11]. Currently the NGA1 product is in operational stage while the NGA2 product is provided for test purposes. The Lantmäteriet GNSS data processing in total includes approximately 680 stations in Sweden, Finland, Norway, Denmark as well as some IGS stations outside of the Nordic area.

[9] CODE = Centre for Orbit Determination in Europe

[10] E-GVAP = The EUMETNET GNSS water vapour programme

[11] Swedish Meteorological and Hydrological Institute

4 Network of Permanent Reference Stations for GNSS (SWEPOS™)

SWEPOS™ is the Swedish national network of permanent GNSS stations operated by Lantmäteriet (Lilje et al., 2014); see SWEPOS website www.swepos.se or through www.lantmateriet.se/swepos.

The purposes of SWEPOS are:

- Providing single- and dual-frequency data for relative GNSS measurements.
- Providing DGNSS[12] corrections and RTK[13] data for distribution to real-time users.
- Acting as the continuously monitored foundation of SWEREF 99.
- Providing data for geophysical research and for meteorological applications.
- Monitoring the integrity of the GNSS systems.

SWEPOS uses a classification system of permanent reference stations for GNSS developed within the NKG. The system includes four different classes; A, B, C and D, where class A is the class with the highest demands.

By May 2017 SWEPOS consisted of totally 381 stations, 39 class A stations and 342 class B ones, see Figures 4.1 and 4.2. This means that the total number of SWEPOS stations has increased with 11 stations since the previous EUREF Symposium one year ago, see Figure 4.3.

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

[12] DGNSS = Differential GNSS

[13] RTK = Real-Time Kinematic

Figure 4.1: *Sveg is one of the SWEPOS stations belonging to class A. It has both a new monument (established in 2011) and an old monument (from 1993).*

Figure 4.2: *Vagnhärad is a SWEPOS station with a roof-mounted GNSS antenna mainly established for network RTK purposes belonging to class B.*

(dual-frequency multi-GNSS receivers with antennas of Dorne Margolin choke ring design), but with somewhat less redundancy.

The 21 original class A stations have two kinds of monuments; the original concrete pillars as well as newer steel grid masts, see Figure 4.1. The new monuments are equipped with individually calibrated antennas and radomes of the type LEIAR25.R3 LEIT.

Five of the original SWEPOS stations (Onsala, Mårtsbo, Visby, Borås and Kiruna) are included in the IGS network, as well as the new monuments at three of them (ONS1, MAR7 and KIR8), which also are included in the IGS-MGEX[14] pilot project.

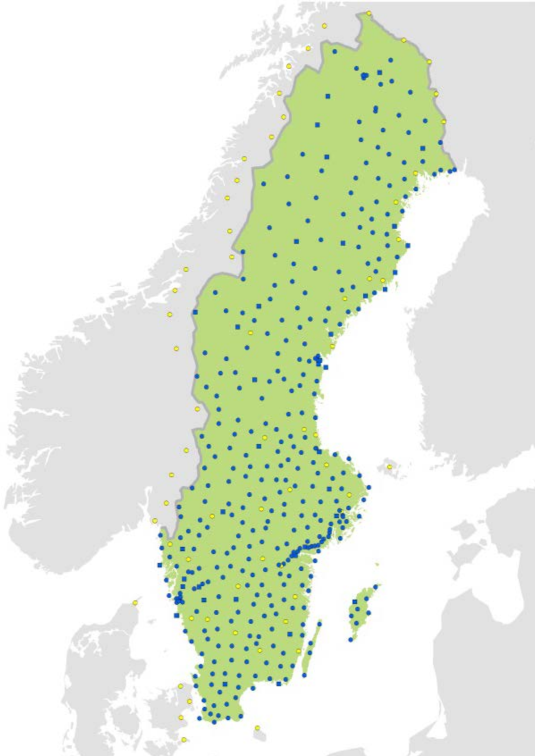

Figure 4.3: *The SWEPOS network in May 2016. Squares indicate class A stations and dots indicate class B ones. Stations in neighbouring countries as well as stations from other service providers in Sweden used in the SWEPOS Network RTK Service are also marked.*

Today all SWEPOS stations are upgraded to track the modernized GPS signals and the new GNSS systems.

5 SWEPOS Services

SWEPOS provides real-time services on both metre level (DGNSS) and centimetre level (network RTK), as well as data for post-processing in RINEX[15] format. The DGNSS service is since 2016, in line with some of the national geographical data from Lantmäteriet, available as open data. An automated post-processing service is also available. This service utilizes the Bernese GNSS Software version 5.2 and takes since 2016 advantage of both GPS and GLONASS.

[14] Multi-GNSS Experiment

[15] RINEX = Receiver Independent EXchange format

Since data from permanent GNSS stations are exchanged between the Nordic countries, good coverage of the network RTK service in border areas and along the coasts has been obtained. Several stations from SATREF in Norway and Danish Styrelsen for Dataforsyning of Effektivisering (Agency for Data Supply and Efficiency) as well as from private operators in Norway, Denmark, Finland and Germany are included. SWEPOS is also using data from 30 Trimble stations inside Sweden.

The service has today (May 2017) approximately 3320 subscriptions, which means some 360 new users since last year. Lantmäteriet has also signed cooperation agreements with three international GNSS service providers, using the data for their own services. This is done in order to increase the use of GNSS data from the SWEPOS stations.

With the main purpose to improve the performance of the network RTK service, a general densification of the SWEPOS network has been going on since 2010 by establishing around 40 new stations each year. The establishment of new stations is since a couple of years on a lower level. More comprehensive densifications have also been performed in some areas to meet the demands for machine guidance in large-scale infrastructure projects.

RINEX 3 is now stored in parallel with RINEX 2 from some stations and the plan is to have RINEX 3 available from all SWEPOS stations during 2017.

The real-time services are utilizing Trimble Pivot Platform GNSS Infrastructure Software and are operating in virtual reference station mode. Galileo network RTK test measurements have successfully been performed during 2016–2017. The implementation of Galileo in the software for the network RTK service as well as distribution of GPS L5 and L2C signals using RTCM MSM is planned during 2017. Code and phase biases in multi-GNSS positioning have also been studied (Håkansson et al., 2016).

6 Implementation of SWEREF 99

SWEREF 99 was adopted by EUREF as the realization of ETRS89 in 2000 (Jivall & Lidberg, 2000) and is used as the national geodetic reference frame since 2007.

By defining SWEREF 99 as an active reference frame we are exposed to rely on the positioning services of SWEPOS, like the network RTK service. All alterations of equipment and software as well as movements at the reference stations will in the end affect the coordinates. In order to be able to check all these alterations, so-called consolidation points have been introduced by Lantmäteriet (Engberg et al., 2010). The approximately 300 so-called SWEREF points are used for this purpose and 50 of them are re-measured each year following a yearly programme. Reprocessing of the measurements of SWEREF points performed during 1998–2015 has recently been done with the GAMIT software, and is in progress with the Bernese GNSS Software. The outcome will be used to analyse the stability of SWEREF 99 and to define the SWEREF 99 component in the fit of the NKG2015 geoid model to SWEREF 99 and RH 2000; see chapter 8.

Station dependent errors at the SWEPOS-stations are limiting factors for height estimation in SWEREF 99. In order to investigate such errors and find corrections for them, station calibration campaigns – in situ calibrations – have been carried out on a selection of the original SWEPOS stations. The analysis revealed height errors of approximately 1 cm for both mast and pillars when not taking the station dependent effects into account in a solution based on ionosphere free linear combination with estimated troposphere parameters (Lidberg et al., 2016).

The work regarding the implementation of SWEREF 99 among different authorities in Sweden, such as local ones, is in a final stage. Almost all of the 290 Swedish municipalities have started the process to replace their old reference frames with SWEREF 99 and actions are taken to start the transition in the remaining ones. The number of municipalities that have finalized the replacement has increased from 282 to 285 during the last year.

7 Implementation of RH 2000

The third precise levelling of the mainland of Sweden lasted 1978–2003, resulting in the new national height system RH 2000 in 2005 (Ågren et al., 2007).

Since the beginning of the 1990's, a systematic inventory/updating of the network is continuously performed. When an update is required, the new levelling is done through procurement procedures, which is also the situation for the remeasurements of the 300 SWEREF points described in chapter 6.

The work with implementing RH 2000 among different authorities in Sweden is in progress (Kempe et al., 2014). Almost 90% of the 290 Swedish municipalities have, mainly in co-operation with Lantmäteriet, started the replacement of their local height systems with RH 2000. So far approximately 230 municipalities have finalized the replacement for all activities, which is approximately 30 more than by the time for the previous EUREF Symposium.

8 Geoid Determination

The current Swedish national geoid model, SWEN08_RH2000, was released at the beginning of 2009. The standard uncertainty of SWEN08_RH2000 has been estimated to 10–15 mm everywhere on the Swedish mainland with the exception of a small mountainous area to the north-west, where the standard uncertainty is larger, probably around 5–10 cm.

According to the strategic plan Geodesy 2010, the ultimate goal is to compute a 5 mm (68%) geoid model by 2020. To reach this goal – to the extent that it is realistic – work is going on to establish a new gravity network/system as well as to improve the Swedish detail gravity data by making new gravity measurements. New measurements have for instance been performed on lake Vänern and in the Swedish mountains to the north-west.

An important geoid activity in the last years has been the *NKG2015 geoid model project*, made in international cooperation under the umbrella of the NKG Working Group of Geoid and Height Systems. The goal has been to compute a new common gravimetric quasigeoid model over the Nordic and Baltic countries. The NKG gravity database for the whole Nordic-Baltic area has been updated and a new NKG GNSS/levelling database and a common DEM were also created. The computations were then made independently by five computation centres, from Sweden, Denmark, Finland, Norway and Estonia, using different regional geoid computation methods, software and set-ups. The modelling method utilized for the final model, which is Least Squares Modification of Stokes' formula with additive corrections, was chosen based mainly on the agreement to GNSS/levelling. The final NKG2015 quasigeoid model was released in October, 2016 (Ågren et al. 2016a). GNSS/levelling evaluations show that the model is a significant step forward, not only compared to previous NKG models, but also with respect to other state-of-the-art geoid models that cover the whole Nordic-Baltic area.

As the next step, a new Swedish geoid model will be computed, which will be called SWEN16_RH2000. It will be derived by adding a smooth residual surface to the gravimetric NKG2015 model. This surface is computed based on a new, updated GNSS/levelling dataset, consisting primarily of those consolidation points (see chapter 6) at which accurate levelled heights are available in RH 2000. As the corresponding heights above the ellipsoid are re-determined every six years using a state-of-the-art GNSS method, the new GNSS/levelling dataset should be considerably more accurate than the old one (utilized for SWEN08_RH2000). It is planned that SWEN16_RH2000 will be released just after the summer 2017.

9 FAMOS and Baltic Sea Chart Datum 2000

Lantmäteriet is also engaged in the EU project FAMOS[16]. The main purpose of FAMOS is to increase the safety of navigation in the Baltic Sea, mainly by finalizing hydrographic surveying in areas of interest for commercial shipping. Other important aims are to improve navigation and hydrographic surveying with GNSS based methods in the future and to support the introduction of the common Baltic Sea Chart Datum 2000 (EVRS with land uplift epoch 2000.0) in the Baltic Sea by 2020 (Ågren et al. 2016b). In FAMOS *activity 2* the main goal is to improve the geoid model in the Baltic Sea area, which will provide an important basis for future offshore navigation.

To reach the goal of an improved Baltic Sea geoid model, new marine gravity data are collected at the hydrographic surveying vessels, to check and improve the existing gravity data as well as to fill gaps. Figure 9.1 illustrates a harbour tie measurement. According to the plan, a new improved and validated FAMOS geoid model will be released by 2020, which will be used to realize the Baltic Sea Chart Datum 2000 out in the Baltic Sea.

In FAMOS, Lantmäteriet is working mainly with activity leading (of activity 2), marine gravimetry, evaluation of existing gravity data/databases and geoid computation. Lantmäteriet has recently procured a ZLS marine gravimeter, which was delivered in April 2017. We further work with connecting the Swedish tide gauges to RH 2000 as well as with evaluating different real-time GNSS navigation methods at sea.

Figure 9.1: *Harbour tie gravity measurement made by Lantmäteriet in the FAMOS project.*

10 Gravity Activities

Absolute gravity observations have been carried out at 14 Swedish sites since the beginning of the 1990’s, see Figure 10.1. All sites, except for Göteborg (Gtbg) which no longer is in use, have been observed by Lantmäteriet since 2007. The observations have been carried out with Lantmäteriet’s absolute gravimeter (Micro-g LaCoste FG5X – 233, which was upgraded in the autumn 2016 to FG5X). The objective behind the investment was to ensure and strengthen the observing capability for long-term monitoring of the changes in the gravity field due to the Fennoscandian GIA[17].

All Swedish absolute gravity sites for FG5 (except for Göteborg) are co-located with reference stations in the SWEPOS network. Skellefteå, Smögen, Visby and Onsala are co-located with tide gauges. Onsala is also co-located with VLBI[18].

Absolute gravity observations have also been performed abroad, mainly in the Nordic countries but also in Serbia, the

[16] FAMOS = Finalising Surveys for the Baltic Motorways of the Sea

[17] GIA = Glacial Isostatic Adjustment

[18] VLBI = Very Long Baseline Interferometry

Republic of Macedonia and in Bosnia and Herzegovina. Furthermore, seven inter-comparisons have been carried out; in Luxembourg, Paris and Wettzell.

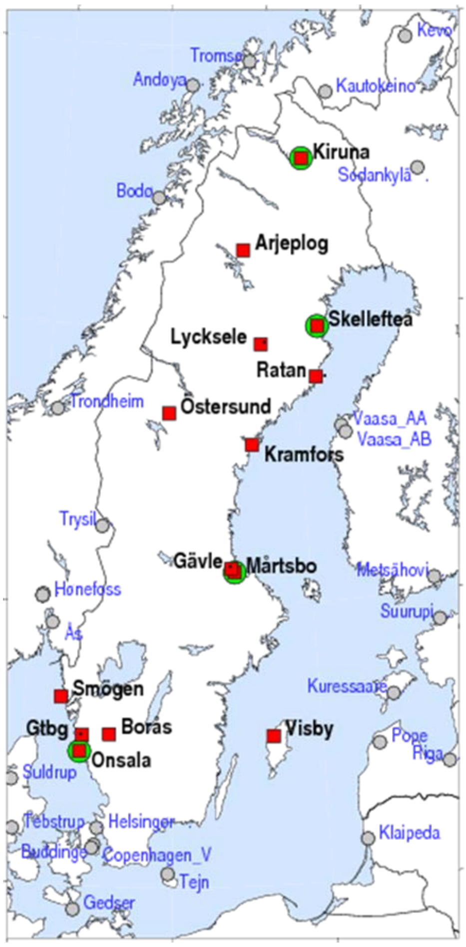

Figure 10.1: *The 14 absolute gravity sites (for FG5) in Sweden (red squares) and sites in neighbouring countries (grey circles). The four sites with time series more than 15 years long have a green circle as background to the red square.*

The establishment of a new Swedish fundamental gravity network is going on (Engfeldt 2016a). The work started in 2011 in co-operation with IGiK[19], using their absolute gravimeter A-10 – 020 for the observations. Until 2015, 97 sites have been measured in co-operation with IGiK.

Some relative measurements and some calculations concerning the land uplift for the FG5 sites remain until it is time to define the system (Engfeldt 2016b).

At Onsala Space Observatory of Chalmers University of Technology, a superconducting gravimeter was installed during 2009. This investment should be seen as an additional important instrument at the Onsala geodetic station, but also in view of the efforts regarding absolute gravity for studying temporal variations in observed gravity. This gravimeter has been calibrated five times by Lantmäteriet's FG5, latest in July 2016.

11 Geodynamics

The main purpose of the repeated absolute gravity observations of Lantmäteriet is to support the understanding of the physical mechanisms behind the Fennoscandian GIA process. One key parameter is the relation between gravity change and geometric deformation (Olsson et al., 2015). A theoretical determination of the relation in Fennoscandia has been done by Olsson et al. (2015) which is about to be verified by comparison of the latest uplift velocity field (see below) to the first combined dataset of absolute gravity measurements. A manuscript is currently in preparation.

Research regarding the 3D geometric deformation in Fennoscandia and adjacent areas is foremost done within the BIFROST[20] effort (Lidberg et al., 2015). Reprocessing of all observations from permanent GPS stations is a continuous activity. A velocity field based on 170 stations using the GAMIT/GLOBK software is currently subject to publication. Works towards a new velocity field based on more than 200 stations are underway using the GAMIT/GLOBK, GIPSY and Bernese software.

The new land uplift model NKG2016LU was released on 30 June 2016. It is developed as a combination and modification of the mathematical (empirical) model of Olav Vestøl and the geophysical model NKG2016GIA_prel0306 developed within

[19] IGiK = Institute of Geodesy and Cartography, Poland

[20] BIFROST = Baseline Inferences for Fennoscandian Rebound Observations Sea level and Tectonics

an NKG activity (Steffen et al., 2014). The geophysical model fits both the recent BIFROST uplift velocity field as well as relative sea-level data equally well. Current work addresses to provide reliable uncertainty estimates for NKG2016LU. Uncertainty of the geophysical model is calculated based on the spread of well-fitting GIA models to the observations within the 1-sigma range of the best-fitting GIA model. The range of GIA models tested include more than 400 different Earth models and 25 different ice history models. The proposed uncertainty for NKG2016GIA_prel0306 is shown in Fig. 11.1 and largely visualizes uncertainties due to unknown ice distribution.

Lantmäteriet is involved in the EUREF working group on *Deformation models* (www.lantmateriet.se/en/Maps-and-geographic-information/GPS-and-geodetic-surveys/Reference-systems/EUREF-working-group-on-Deformation-models), which aims at obtaining a high resolution velocity model for Europe and adjacent areas and significantly improving the prediction of the time evolution of coordinates. This will help overcome the limitations in the use of ETRS89 and also lead to a general understanding of the physics behind such a velocity field. The velocity

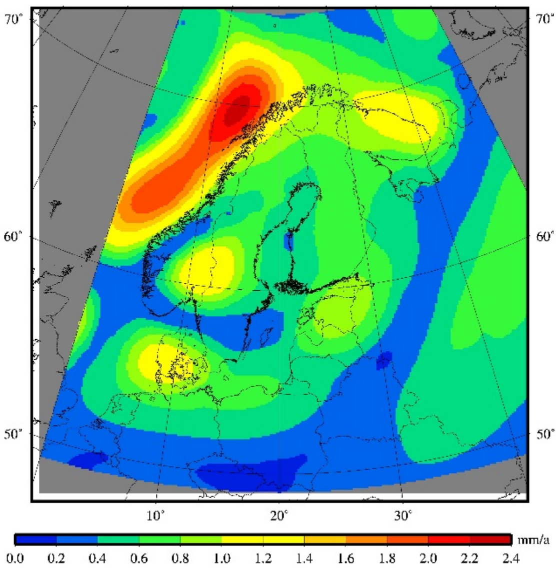

Figure 11.1: *Uncertainty of the geophysical model NKG2016GIA_prel0306. Unit in mm/a.*

model including deformations will be developed once the densified EPN velocity field becomes available this year.

Since January 2015, Lantmäteriet contributes via a Service Level Agreement to the EU-financed Horizon 2020 project EGSIEM[21]. Here, the global GIA correction for gravity missions such as GRACE is provided by Lantmäteriet. This correction is based on a combination of several regional ice history models with their corresponding Earth models. The correction shall also include uncertainty estimates from the modelling. A test version was presented in January 2017 and the first official version, yet without uncertainty estimates, shall be implemented in the EGSIEM service in June 2017.

12 Further Activities

The regulatory documents for Lantmäteriet states that one of its responsibilities is to contribute to efficient and standardized surveying and mapping in Sweden. One of the means to accomplish this is through a series of best-practice guidelines called HMK (a Swedish acronym roughly translated as "Guidelines for mapping and surveying"). HMK covers a wide variety of methods for geodata capture (e.g. laser scanning, aerial photography, geodetic surveying) as well as more general information about quality parameters and how they should be specified. Updates are published on an annual basis, and additional guidelines are added as new techniques emerges. Geodetic applications are covered in five documents:

- Geodetic infrastructure
- Control surveying
- Terrestrial detail surveying
- GNSS-based detail surveying
- Support for tendering and choice of surveying methods

[21] EGSIEM = European Gravity Service for Improved Emergency Management

All HMK guidelines are published online at www.lantmateriet.se/hmk and can be downloaded free of charge.

Sweden (and Lantmäteriet) organized the NKG Summer School in Båstad on 29 August to 1 September, 2016, with approximately 75 participants. The theme was GNSS and more information can be found at www.lantmateriet.se/nkg2016. The Summer School is arranged every four years in one of the Nordic countries.

Lantmäteriet is also responsible for the production of a new Swedish national elevation model. The mainly used method for the data capture is airborne laser scanning and the production started in July 2009. 97 % of the Swedish territory has so far been scanned, where the remaining parts are mostly in the mountainous part of Sweden, where the weather conditions are unstable. The scanning is expected to be finalized during 2017. There are also preparations going on in order to obtain repeated coverage in cooperation with the Swedish Forest Agency and the forest industry.

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

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