National Report of Sweden to the EUREF 2019 Symposium

– geodetic activities at Lantmäteriet

T. KEMPE, A. ALFREDSSON, L. ALM, A. ENGFELDT, B. EURENIUS, L. JIVALL, M. LIDBERG , M. LILJE, T. NING , D. NORIN, P-A. OLSSON, H. STEFFEN, P. WIKLUND, J. ÅGREN

Lantmäteriet, SE-801 82 Gävle, Sweden
geodesi@lm.se

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1 Introduction

Lantmäteriet, the Swedish mapping, cadastral and land registration authority, is responsible for the national geodetic infrastructure. The geodetic work is based on the new geodetic strategic plan presented late 2018 (Lantmäteriet, 2018). 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], EPOS[3], IGS[4] and MGEX[5] and international analyses of GNSS data
- the implementation and sustainability of the Swedish national reference frame SWEREF 99 and the national height system RH 2000 (ETRS[6]89 and EVRS[7] realisations respectively)
- improvements of Swedish geoid models and renovation of the gravity network.

Sweden, through Lantmäteriet, is since 2018 member of the UNGGIM SCoG[8] and is also leading its working group on Education, Training and Capacity Building.

2 Contributions from Lantmäteriet to EPN

The number of SWEPOS stations included in EPN is 27. Seven of the original SWEPOS stations have been included since the very beginning of EPN These stations are Onsala, Mårtsbo, Visby, Borås, Skellefteå, Vilhelmina and Kiruna (ONSA, MAR6, VIS0, SPT0, SKE0, VIL0 and KIR0). The other 20 stations are represented by an additional monument located at the original SWEPOS stations. Daily and hourly data are delivered for all stations, while real-time data are delivered from nine stations.

Lantmäteriet operates the NKG[9] EPN AC[10] in cooperation with Onsala Space Observatory. The NKG AC contributes with weekly and daily solutions, since March 2019 based on final CODE[11] MGEX products, using the Bernese GNSS Software. The EPN sub-network processed by the NKG AC consists of 97 reference stations (of which two presently are inactive) (May 2019) concentrated to northern Europe.

[1] Global Navigation Satellite Systems

[2] EUREF Permanent Network

[3] European Plate Observing System (https://www.epos-ip.org/)

[4] International GNSS Service

[5] Multi-GNSS Experiment

[6] European Terrestrial Reference System

[7] European Vertical Reference System

[8] United Nations initiative on Global Geospatial Information Management, Subcommittee on Geodesy

[9] Nordic Geodetic Commission (Nordiska kommissionen för geodesi)

[10] Analysis Centre

[11] Centre for Orbit Determination in Europe

3 EPN related GNSS Analysis

The NKG GNSS analysis centre is chaired by Lantmäteriet (Lahtinen et al., 2018). The project aims at a dense 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. 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 has been done and resulted in a densified coordinate and velocity solution in ITRF 2014 (Lahtinen et al., 2019). The weekly solutions from the reprocessing have also contributed to the EPN densification project.

In June 2016 Lantmäteriet became one of the analysis centres in E-GVAP[12] and undertakes the data processing in order to provide NRT[13] ZTD[14] (Lindskog et al., 2017). Both the Bernese GNSS Software version 5.2 and GIPSY/OASIS II version 6.2 are used for the processing. The latter software uses the PPP[15] strategy and approximately 700 reference stations in total, situated mainly in Sweden, Finland, Norway and Denmark, are processed.

4 SWEPOS – the National Network of Permanent Reference Stations for GNSS

SWEPOS™ is the Swedish national network of permanent GNSS stations operated by Lantmäteriet; see the SWEPOS website, www.swepos.se.

The purposes of SWEPOS are

- providing single- and dual-frequency data for relative GNSS measurements
- providing DGNSS[16] corrections and RTK[17] 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.

By May 2019 SWEPOS consisted of totally 421 stations, of which 48 are of a higher class, the so-called class A, and the remaining 373 stations are of class B, see Figure 4.1 and Figure 4.2. This means that the total number of SWEPOS stations has increased with 23 stations since the previous EUREF Symposium.

Figure 4.1: *Sveg is one of the SWEPOS class A stations. It has an old monument (established in 1993) as well as an additional monument (2011).*

The class A stations are monumented on bedrock and have redundant equipment for GNSS observations, communications, power supply etc. Class B stations are mainly established on top of buildings for network RTK purposes. They have the same instrumentation as the class A stations (dual-frequency multi-GNSS receivers with choke ring antennas), but with somewhat less redundancy.

[12] The EUMETNET GNSS water vapour programme

[13] Near Real-Time

[14] Zenith Total Delay

[15] Precise Point Positioning

[16] Differential GNSS

[17] Real-Time Kinematic

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

Five of the original 21 SWEPOS stations (Onsala, Mårtsbo, Visby, Borås and Kiruna) are included in the IGS network, as well as three of the additional monuments with newer steel grid masts (ONS1, MAR7 and KIR8), which also are included in IGS-MGEX.

5 SWEPOS Services

SWEPOS provides real-time services of metre level uncertainty (DGNSS) and centimetre level uncertainty (network RTK), as well as data for post-processing in RINEX[18] format. A transition from RINEX 2 to RINEX 3 has during the last years been implemented and is now almost finalised for all SWEPOS stations. An automated post-processing service, based on the Bernese GNSS Software, is also available.

Since data from permanent GNSS stations are exchanged between the Nordic countries, good coverage of the network RTK service has been obtained in border areas and along the coasts. Several stations from SATREF in Norway and the Danish Agency for Data Supply and Efficiency are included together with stations from private operators in Norway, Denmark and Finland as well as Sweden.

The network RTK service has, in May 2019, approximately 4450 subscriptions, which means some 700 additional users since last year. Lantmäteriet has also signed cooperation agreements with four international GNSS service providers using data from SWEPOS stations for their services. This is done to increase the use of SWEPOS data as well as optimising the benefits of the geodetic infrastructure.

The real-time services utilise Trimble Pivot Platform GNSS Infrastructure Software and are operating in virtual reference station mode. The network RTK service distributes data for GPS, GLONASS and Galileo as well as GPS L5 and L2C signals using RTCM[19] MSM[20]. The plan is to include BeiDou during 2020.

There is an increasing demand for uninterrupted availability of the real-time services, from current applications (e.g. agriculture), as well as future applications (e.g. autonomous vehicles). To meet these demands, a redundant server infrastructure is built in a separate physical location, protecting against e.g. loss of electricity or Internet connectivity. It will also facilitate system maintenance, since all traffic can be redirected to the other location while e.g. updating is done.

6 Reference Frame Management – SWEREF 99

SWEREF 99 was adopted by EUREF as the Swedish realisation 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

[18] Receiver Independent Exchange format

[19] Radio Technical Commission for Maritime Services

[20] Multiple Signal Message

equipment and software as well as movements at the reference stations will in the end affect the coordinates. To be able to check all these alterations, approximately 300 nationally distributed passive so-called consolidation points are used. Each year, 50 of them are remeasured with static GNSS following a yearly programme.

The main part of the consolidation points were established as so-called SWEREF points during the RIX 95 project (Andersson et al., 2015). In 2018, a review of the set of consolidation points was performed (Alfredsson et al. 2019). A number of consolidation points will be replaced to improve the Swedish national GNSS/levelling dataset (see chapter 8). Out of the 300 points, approximately 120 points will be replaced and co-located with height benchmarks.

In 2017-2018, a reprocessing of all SWEREF/consolidation point measurements (1996-2016) was performed in order to get a consistent set of coordinates. All measurements have been done for 2x24 hours using choke ring antennas, where the original processing was done in the Bernese GNSS software and the reprocessing was done with both the Bernese GNSS software and the GAMIT software. Based on this, the stability of SWEREF 99 has, so far, been analysed in Jivall et al. (2019).

The coordinates of the SWEPOS stations (see chapter 4) have regularly been updated for equipment changes and antenna model changes; lately the switch from IGb08.atx to IGS14.atx. Corrections have been added in a cumulative way and stations have been determined in different epochs, partly using different deformation models, leading to an increase of the uncertainties between stations. During 2019 we will review the SWEREF 99 coordinates at the SWEPOS stations and investigate the possibilities for a solution that is more consistent with the present situation.

The work regarding the implementation of SWEREF 99 among different authorities in Sweden, such as local ones, is almost finalised (two of the 290 Swedish municipalities still remain to replace their old reference frames with SWEREF 99).

7 Maintenance of the National Levelling Network

The third precise levelling of the mainland of Sweden lasted 1979–2003, resulting in the new national height system RH 2000 in 2005 (Ågren et al., 2007).

Our assessment is that RH 2000 will be the national height system for many years to come and that it will be based on levelling. The motive is that the precision of height determination with GNSS (height above the ellipsoid) is not as accurate as the levelling technique. Therefore, the maintenance of the height control network needs to be continued for the foreseeable future.

Since the beginning of the 1990s, a systematic inventory/updating of the network is continuously performed and during 2018 a review of the updating programme was performed (Alfredsson et al. 2019). When an update is required, the new levelling is done through procurement procedures, which is also the situation for the remeasurements of the 300 consolidation points described in chapter 6.

The implementation of RH 2000 among different authorities in Sweden is in progress (Kempe et al., 2014). About 90% of the 290 Swedish municipalities have now replaced their local height systems with RH 2000.

8 Geoid Determination

According to Lantmäteriet's strategic plan (Lantmäteriet, 2018), an important goal is to compute a seamless geoid model of high accuracy that fulfils the needs of users both on land and at sea. Many activities are going on to realize this. A new gravity reference system/frame RG 2000 has recently been finalised (see chapter 10). New Swedish detail gravity observations are continuously being collected using Scintrex CG5 with the purpose to fill gaps or replace old data of low quality. New measurements have, for instance, been made on lake Vänern and in the rough Swedish mountains to the north-west. An important activity is further the work made in FAMOS to improve gravity and geoid in the Baltic Sea (see chapter 9), which we can also benefit from on land, mainly in the coastal areas.

An important step in the last few years has been the NKG2015 geoid model project, which was made in international cooperation under the umbrella of the NKG Working Group of Geoid and Height Systems. In this project, a new common gravimetric quasigeoid model was computed over the whole Nordic and Baltic area. In connection with this, the NKG gravity database was thoroughly cleaned/updated, and a new NKG GNSS/levelling database and a common DEM[21] were created. 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 for instance EGM2008, EGG2015 and EIGEN-6C4.

In the last years, much work has been spent on improving the Swedish national GNSS/levelling dataset. The core of the new, updated dataset is the so-called SWEREF points for which accurate levelled heights are available in RH 2000. A majority of these SWEREF points are the consolidation points mentioned in chapter 6, which are re-determined every six years. This makes it possible to detect and remove unstable points. The final GNSS heights above the ellipsoid were determined as the weighted mean of the different epochs and processing results (i.e. two Bernese datasets and one GAMIT dataset).

The new Swedish national geoid model SWEN17_RH2000 was released in October 2017. It was computed by adapting the gravimetric NKG2015 geoid (slightly corrected over Sweden only with the latest Swedish data) to the above improved set of GNSS/ levelling observations by adding a smooth residual surface computed by least squares collocation. The standard uncertainty of SWEN17_RH2000 is estimated by cross validation to 8-10 mm on the Swedish mainland and on the large Baltic Sea islands Öland and Gotland. This is a significant step forward compared to the old model SWEN08_RH2000, but still more work is required to reach the ultimate 5-mm goal.

In the coming years, the levelled normal heights of the above GNSS/levelling points will be checked by relevelling relative to the benchmarks in the national precise levelling network. Otherwise, most of Lantmäteriet's efforts are right now being spent on improving the geoid model at sea, and in the border between land and sea; see next chapter.

9 Marine gravity measurements in the Baltic Sea (FAMOS)

Since 2015, Lantmäteriet has been engaged in the EU project FAMOS[22]. The main purpose of FAMOS is to increase the safety of navigation in the Baltic Sea, mainly by finalising 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 (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 GNSS-based offshore navigation. To reach the goal of an improved Baltic Sea geoid model, new marine gravity data are collected over sea to check and improve the existing gravity data as well as

[21] Digital Elevation Model

[22] Finalising Surveys for the Baltic Motorways of the Sea

to fill gaps. According to the plans, a new improved and validated FAMOS geoid model will be released by 2022.

From mid-2019, the FAMOS project will take a break until the next sub-project starts. Lantmäteriet nevertheless continues with gravity measurements in the Baltic Sea. (The FAMOS efforts are very much in line with Lantmäteriet's internal goals to derive a seamless geoid model of high accuracy both on land and at sea.)

In 2017, Lantmäteriet procured a ZLS marine gravimeter in the FAMOS project. In 2018, this gravimeter was used to observe four marine campaigns and one airborne ditto. The Kattegat airborne campaign was made together with the Danish colleagues from DTU Space and is illustrated in Figure 9.1 and Figure 9.2.

Figure 9.1: *The airborne Kattegat campaign in October 2018: Installation of Lantmäteriet's ZLS dynamic gravity meter™ in the airplane.*

The plan is to observe four 10-days dedicated marine campaigns in 2019, which will constitute a large step forward.

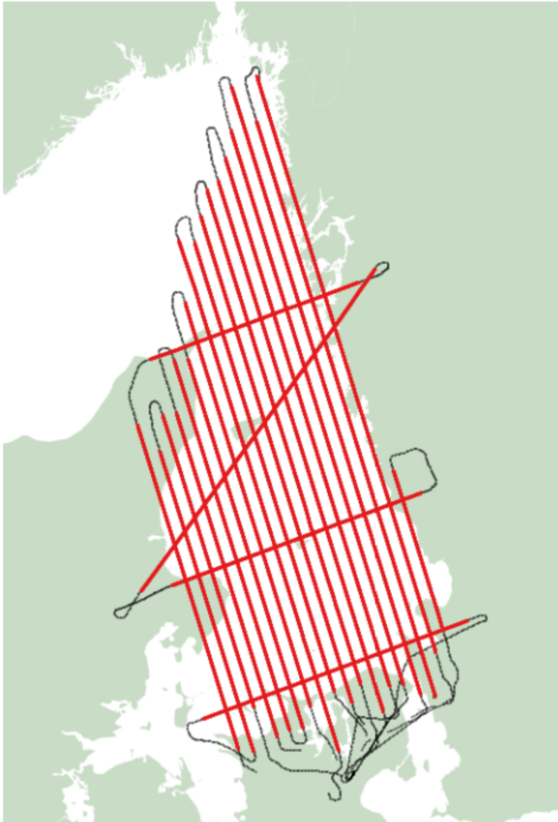

Figure 9.2: *The routes flown during the airborne Kattegat campaign, of which the red lines were used in the processing.*

10 Gravity Activities

Postglacial gravity change in Fennoscandia is studied by means of repeated absolute gravity (AG) observations in long time series (Olsson et al., 2019). In Sweden 13 stations (see Figure 11.1) are revisited with Lantmäteriet's absolute gravimeter, FG5X-233, with an interval of approximately one to three years. Since 2007, FGX-233 also regularly participates in local, regional and international AG intercomparisons in order to keep track of possible systematic biases.

All Swedish absolute gravity sites for FG5 are co-located with SWEPOS stations. Ratan, Skellefteå, Smögen, Visby and Onsala are co-located with tide gauges. Onsala is also co-located with VLBI[23] telescopes and a superconducting gravimeter, which is annually calibrated with FG5X-233 AG observations.

[23] Very Long Baseline Interferometry

In the beginning of 2018 the new Swedish gravity reference frame, RG 2000, became official (Engfeldt et. al., 2019). The reference level is as obtained by absolute gravity observations according to international standards and conventions. It is a zero permanent tide system in post glacial rebound epoch 2000. RG 2000 is realised by the 13 FG5 stations mentioned above, 96 A10 points (measured by IGiK[24]) and some 200 points observed with relative gravimeters; see Figure 10.1.

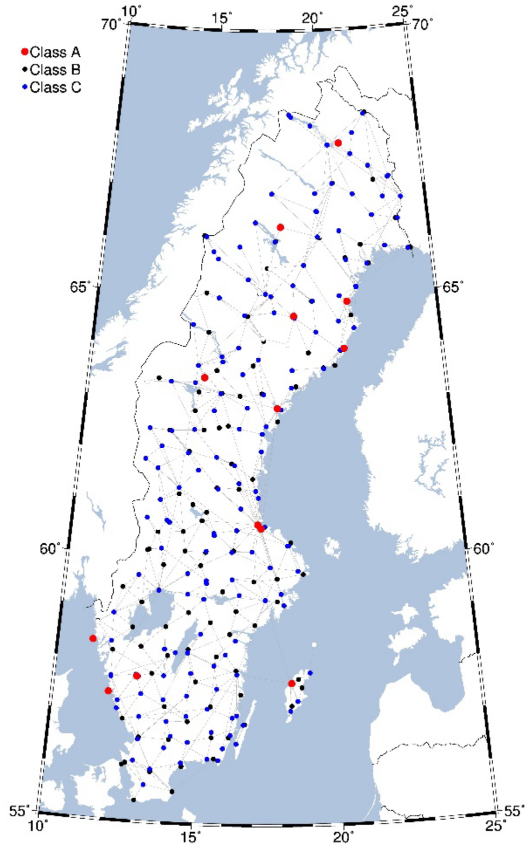

Figure 10.1: *Reference points in RG 2000 (class A, B, C).*

11 Geodynamics

The main purpose of Lantmäteriet's repeated absolute gravity observations is to support the understanding of the physical mechanisms behind the Fennoscandian GIA[25] process. Olsson et al. (2019) present the first combined, open accessible database of three decades of absolute gravity observations in the Nordic and Baltic countries. They also introduce NKG2016LU_gdot (see Figure 11.1), a model of GIA-induced gravity rate of change in Fennoscandia that is achieved by means of the NKG2016LU land uplift model, together with the geophysical relation between gravity rate of change and uplift recommended in Olsson et al. (2015).

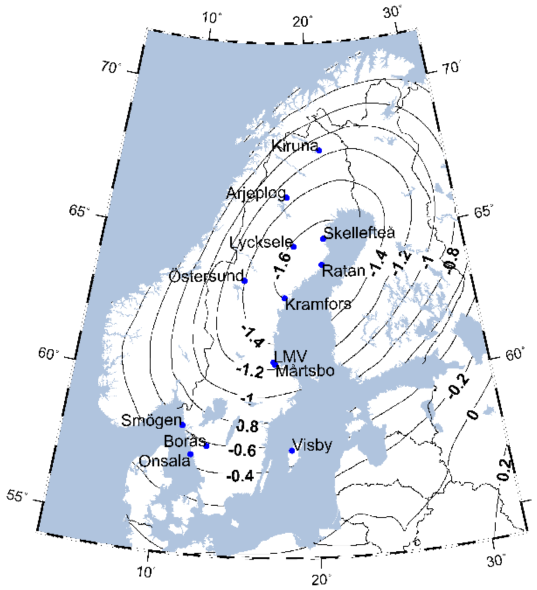

Figure 11.1: *The 13 absolute gravity stations (for FG5) in Sweden (blue dots) with the land uplift model NKG2016LU_gdot, which shows the annual gravity change [μGal yr^{-1}].*

Research regarding the 3D geometric deformation in Fennoscandia and adjacent areas is foremost done within the BIFROST[26] effort (Lidberg et al., 2015). A reprocessed velocity field based on 170 stations using the GAMIT/GLOBK software is currently subject to publication and will contain a detailed analysis of different geodynamic processes that generate the 3D velocity field in northern Europe.

The land uplift model NKG2016LU was released in 2016. Reliable uncertainty estimates have been introduced and will be available immediately after acceptance of the corresponding peer review publication.

[24] Institute of Geodesy and Cartography, Poland

[25] Glacial Isostatic Adjustment

[26] Baseline Inferences for Fennoscandian Rebound Observations Sea level and Tectonics

The new 3D velocity model NKG_RF17vel for northern Europe is currently in preparation. The uplift part is based on NKG2016LU while the horizontal motions are generated from an updated four-layer GIA model that reduces the misfit in the horizontals. This GIA model includes a sub-lithospheric high-viscosity layer.

Lantmäteriet is involved in the EUREF working group on Deformation models (https://www.lantmateriet.se/en/maps-and-geographic-information/GPS-och-geodetisk-matning/Referenssystem/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. A test deformation model was developed with the least-squares collocation method and taking plate boundaries into account. A preliminary version of the densified EPN velocity field was used as input.

Another major activity is the generation of the strain-rate product within EPOS. The project is currently in the implementation phase and is expected to be operational from 2020 onwards. In cooperation with a few institutes in Europe, Lantmäteriet will calculate strain-rate grids for Europe targeted in resolution due to GNSS station distribution and area of interest.

In a geodynamic study regarding the effects of GIA, modelling results from Lantmäteriet were among others used to identify GIA as a likely trigger of recent earthquakes in northern Germany (Brandes et al., 2019).

12 Further Activities

In the beginning of 2019, a number of new Digital Geodetic Archive services were released. The services provide information about the national geodetic control points as open data (under CC0 licence):

- A web self-service: https://stompunkt.lantmateriet.se.
- A WMS[27], which supplies the information in raster format, for import into users' own GIS.
- A direct access service providing information via M2M[28], for integration of data in the users' own applications.

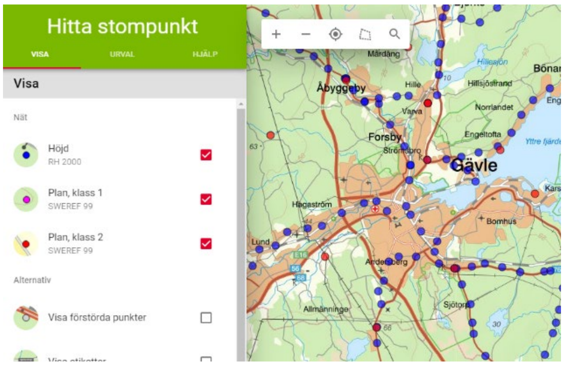

Figure 12.1: *Screenshot from the Digital Geodetic Archive web self-service "Hitta stompunkt".*

Besides the Digital Geodetic Archive, Lantmäteriet also hosts the analogue Geodetic Archive, founded in 1805. It contains data and documents regarding the basic geodetic measurements of Sweden from around 1750 up till now.

During 2019 the review of the Geodetic Archive was completed, and the structure of the information is now in accordance with Swedish archive regulations.

The regulatory documents for Lantmäteriet states that one of its responsibilities is to contribute to efficient and standardised 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. The geodetic

[27] Web map service

[28] Machine to machine communication

documents are revised by a stakeholder reference group and published on a bi-annual basis. The guidelines are supplemented by technical reports that cover various topics more in-depth, 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.

All HMK guidelines are published online at http://www.lantmateriet.se/hmk. The five documents covering geodesy were updated during 2017 and can be downloaded free of charge.

The blurred line between national and local infrastructure has increased the need for stakeholder cooperation. Lantmäteriet is supporting municipalities to put forth surveying strategies where the future need for geodetic infrastructure is thoroughly examined, and positioning systems for large-scale construction projects are designed in cooperation between Lantmäteriet and the Swedish Transport Administration.

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