On the Management of Reference Frames in Sweden

Christina KEMPE, Lotti JIVALL, Martin LIDBERG, Mikael LILJE,
Sweden

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SUMMARY

The national reference frames in Sweden comprise the three-dimensional SWEREF 99 and the height system RH 2000. SWEREF 99 is the national realization of ETRS89, realized by the CORS network SWEPOS™. RH 2000 is realized by the benchmarks established through the extensive third national precise levelling project. There is also a geoid, or height correction, model to relate SWEREF 99 ellipsoidal heights and RH 2000 normal heights.

Both of these reference frames are deformed with time, due to the post-glacial land uplift in Fennoscandia. The main deformation of course occurs in the vertical component, but over time there also is a non-negligible deformation of the horizontal.

SWEREF 99 coordinates and RH 2000 heights are in principle fixed to the values of the original realization (at the epochs 1999.5 and 2000.0, respectively), i.e. coordinates and heights are static. Velocity models are used to obtain SWEREF 99 coordinates in the epoch of the realization, but these velocities are not included in the system definition. Instead, the velocity models are seen as subjects of improvement, allowing introduction of new velocity models without having to re-define the reference frame.

The motivation for choosing a reference frame strategy where coordinates and heights are in principle fixed is above all that the user community is used to "static coordinates" and would prefer to keep it that way. The existing velocity models – horizontal as well as vertical – have been sufficient until recently.

There is on-going work to develop a new land uplift model and in this work the horizontal component is also considered. The plan is to release the new velocity models (horizontal and vertical) in 2016. The plan is to publish also a new geoid model in 2016.

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1. INTRODUCTION

The national reference frames in Sweden comprise the three-dimensional SWEREF 99 and the height system RH 2000. SWEREF 99 is the national realization of ETRS89 (European Terrestrial Reference System), while RH 2000 is the national realization of the European Vertical Reference System (EVRS). Both of these reference frames are deformed with time due to the post-glacial land uplift in Fennoscandia.

The paper deals with the chosen strategy to manage and maintain the reference frames to obtain sustainability in benefit of the user community, as well as the development of velocity fields to be used for the maintenance of the reference frames.

2. BACKGROUND

During the late nineties, there was a discussion within Lantmäteriet, the Swedish mapping, cadastral and land registration authority, whether the national reference frame, based on Bessel's ellipsoid, should be replaced by a globally aligned reference frame. The importance of a sustainable reference frame, appropriate for a long time, was then emphasized. The predecessor of SWEREF 99, SWEREF 93, was not officially approved by the European community and it differed (at the 5 cm level) to the ETRS89 realizations in the neighbouring countries, and therefore it was decided to create a new ETRS89 solution – SWEREF 99. (Jivall & Lidberg, 2000)

The need of a third national precise levelling was discussed in Sweden during the early seventies, when it was clear that the present height system did not fulfil the demands of a national height system. The levelling was performed during 25 years, from 1979 to 2003. It was decided that the adjustment of the new levelling network – resulting in the new height system RH 2000 – should be adapted to minimise the differences to EVRS.

The introduction of, and transition to, the new reference frames in the 290 local authorities and the user community has now been going on for almost 15 years (Alfredsson et al., 2010; Kempe et al., 2014).

2.1 SWEREF 99

SWEREF 99 is the Swedish realization of ETRS89, performed in accordance with the EUREF (IAG Subcommission for Europe) guidelines. SWEREF 99 was adopted as an improvement and extension of ETRS89 at the EUREF Symposium held in Tromsø, 22-24 June 2000.

SWEREF 99 is realized through the national CORS (continuously operating reference station) network. The 21 fundamental SWEPOS stations, monumented with pillars on stable bedrock, define the SWEREF 99 reference frame. All CORS stations that were operational during the summer of 1999 in Sweden (SWEPOS), Norway (SATREF), Finland (FinnRef) and Denmark, totally 49 stations, were included in the SWEREF 99 campaign. From SWEPOS, data for the GPS weeks 1014-1019, (June 13-July 24, 1999) were used and from the foreign stations, 2-3 weeks of data were used (GPS weeks 1014-1015 and 1019). (Jivall & Lidberg, 2000)

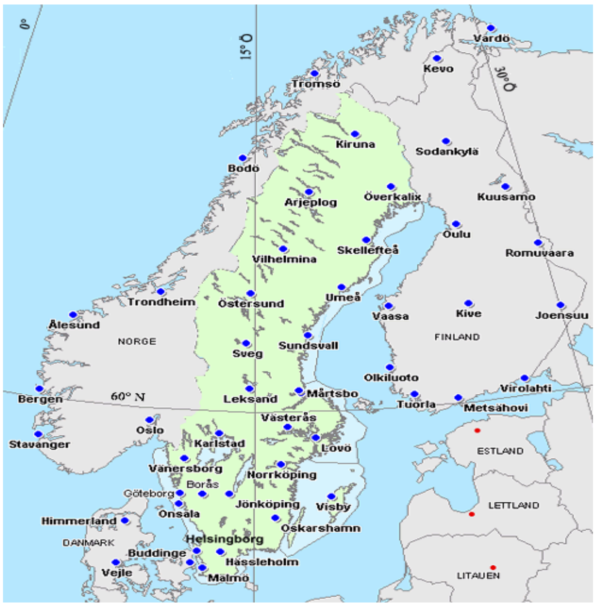

Figure 1: *The reference stations included in the SWEREF 99 campaign.*

The SWEREF 99 solution was computed in ITRF97 epoch 1999.5 and then converted back to ETRS89 in compliance with the EUREF guidelines (Boucher & Altamimi, 1998), implying that the epoch for plate tectonics is 1989.0 and the epoch for intraplate deformations is 1999.5.

2.2 RH 2000

The national height system RH 2000 is realized by the benchmarks from the third precise levelling. The network consists of approximately 50 000 km double run precise levelling and 50 800 benchmarks. The distance between the benchmarks is about 1 km along the levelling lines. The network covers the country in closed loops, with a circumference of approximately 120 km in populated areas.

Figure 2: *The levelling network realizing RH 2000.*

The levelling lines are also connected to the levelling lines of Sweden’s neighbouring countries. This results in closed loops along the borders, making it possible to extend the network around the Baltic Sea, the so-called Baltic Levelling Ring (BLR).

The main reason to define RH 2000 as the Swedish realization of

the EVRS was to have a system that agrees as well as possible with other European systems. The differences to the corresponding height systems in Norway and Finland are within 2 mm along the Swedish border. The new height system in Denmark was introduced before the BLR was adjusted and thus the difference to RH 2000 is larger; approximately 2 cm. (Ågren & Svensson, 2007)
However, the EVRS definition did not state how to treat the post-glacial land uplift, meaning that this issue had to be taken care of at the Nordic level. Since the post-glacial rebound is a significant phenomenon, the system definition for RH 2000 should specify how to handle the land uplift. Hence it was decided at the Nordic level, within the Nordic Geodetic Commission (NKG), that the reference epoch for the reduction of post-glacial rebound is 2000.0, and that the postglacial land uplift model is NKG2005LU (cf. section 3.1). (Svensson et al., 2006)

3. RERENCE FRAME MANAGEMENT IN SWEDEN

The International Federation of Surveyors (FIG) defines three types of modern national reference frames in their publication Reference Frames in Practice Manual (FIG, 2014):

- *Static geodetic reference frame*: Aligned with an ITRF realization at a fixed (reference) epoch. The system must be regularly updated if the defining points move relative to the tectonic plate, e.g. in case of tectonic processes or other deformations such as post-glacial land uplift. For precise GNSS positioning, local CORS or local transformation using geodetic markers must be utilized to obtain coordinates that are “fixed” over time, for a given object.
- *Dynamic (or kinematic) reference frame*: ITRF is a dynamic reference frame, consisting of coordinates and velocities. The principal limitation is the difficulty to integrate data captured over very long time-spans, unless a precise deformation model is utilized.
- *Semi-dynamic reference frame*: Basically a dynamic reference frame, but a deformation model is part of the system definition. GNSS positioning is done in the latest ITRF, current epoch, and the resulting coordinates are propagated back to the given reference epoch, using the deformation model. An advantage of this approach is that data analysis is not degraded due to insufficient modelling of deformations. From the end user’s point of view, the reference frame seems static at the reference epoch.

However, the definition of SWEREF 99 does not really fit into any of these categories. SWEREF 99 coordinates – as well as RH 2000 heights – are in principle fixed to the values of the original realization, at the epoch 1999.5 (and 2000.0, respectively), i.e. coordinates are static.

SWEREF 99 is deformed over time, and the coordinates would need to be regularly updated if we regard SWEREF 99 as a static reference frame. But since there is no intention to update the co-ordinate values of the original realization, SWEREF 99 should rather be considered a semi-dynamic reference frame according to the FIG definition.

Deformation models are indeed used to obtain SWEREF 99 coordinates in the epoch of the realization, but these velocities are not included in the system definition. Instead, the velocity models are seen as subjects of improvement, allowing introduction of new velocity models without having to re-define the reference frame. Therefore SWEREF 99 does not really fit into the semi-dynamic reference frame definition either.

For precise applications, a correct handling of the velocities/epochs is always carefully performed when transforming positions in ITRF, present epoch, to coordinates in SWEREF 99 and/or RH 2000.

The national network RTK service today utilizes the recent velocity model to handle the horizontal and vertical movements, in order to model the error sources in a better way.

3.1 Land uplift model – NKG2005LU

The present land uplift model, NKG2005LU, is a combination of Vestøl's mathematical land uplift model (Vestøl, 2007) and Lambeck's geophysical model (Lambeck et al., 1998).
The reasons for combining the models into one are mainly

- Lambeck's model covers the whole Baltic Levelling Ring in a reasonably realistic way, while Vestøl's model does not
- Vestøl's model fits the observations acquired in the Nordic countries in a better way than Lambeck's model.

NKG2005LU consists of a smoothed version of the Vestøl model in the central parts of the land uplift area, and outside this a smooth transition to Lambeck's model has been done. (Svensson et al., 2006; Ågren & Svensson 2007)

3.1.1 Lambeck's geophysical model

A geophysical model provides a geophysically meaningful model of the land uplift phenomenon. In this case it has also been tuned to the apparent uplift observed by tide gauges, some lake level observations and ancient shore lines. Unfortunately, the Lambeck, Smither and Ekman (1998) model was only available as an image from a publication, so it had to be digitized for the purpose. The digitized version has then been referred to as Lambeck's model.

Investigations showed that the model is biased in the interior parts of Sweden, and due to this it was decided not to use Lambeck's model on its own. It was not possible, though, to compute a new geophysical model for the adjustment of RH 2000. Therefore it was decided to combine Lambeck's model with a mathematical (or empirical) model, for the areas where better information was available. (Svensson et al., 2006)

3.1.2 Vestøl's mathematical model

The mathematically defined surface has been constructed to fit different types of land uplift observations (Vestøl, 2007). In this case, observations from tide gauges, permanent GPS stations and repeated levellings in Finland, Norway and Sweden have been used.

The model fits well with the observations, but is only defined for parts of the whole Baltic Levelling Ring, because only a few observations outside the Nordic area are included. (Svensson et al., 2006)

3.2 Velocity model NKG_RF03vel

NKG_RF03vel was developed to include intraplate deformation in transformations between ITRF (via the NKG 2003 campaign) and the Nordic national realizations of ETRS 89. (Nørbech et al., 2006)

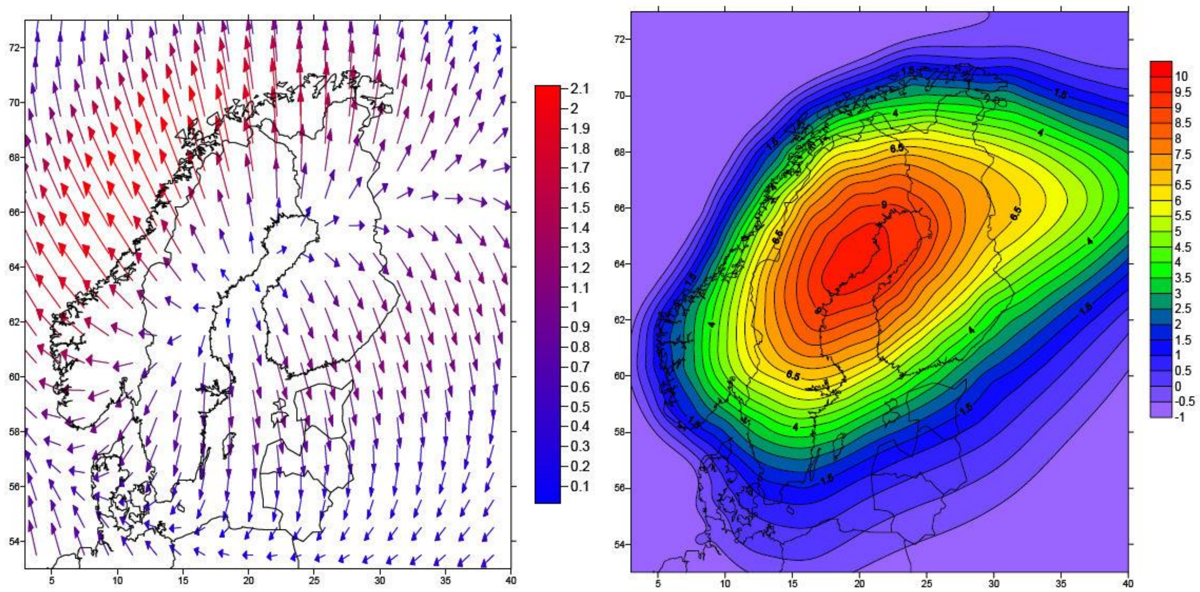

Figure 3*: The NKG_RF03vel velocity model.*

The north and east components origin from the Glacial Isostatic Adjustment (GIA) model presented in Milne (2001). The velocity field from this model has been transformed to the GPS-derived velocity field described in Lidberg et al. (2007); see further Lidberg et al. (2006). Thus, the horizontal velocity field in the grid files describes horizontal displacements relative to stable Eurasia as defined by the ITRF2000 and its rotation pole for Eurasia (Altamimi et al., 2003).

For the up component the absolute version of NKG2005LU model is used. The conversion from apparent land uplift to absolute land uplift takes into account the absolute sea level rise and the geoid rise.

3.3 Geoid models

To facilitate height determination by GNSS, there are national geoid models connected to RH 2000. The geoid models are used to relate GNSS heights above the ellipsoid (SWEREF 99) to normal heights in RH 2000.

In this case, the term ‘geoid model’ is used in a rather loose sense. It does not only denote the actual geoid undulation but also certain – small when compared to the geoid undulation – corrections that are included in the model. As RH 2000 heights are normal heights, it would also be more correct to use the term ‘quasi-geoid model’. However, it was expected that the term ’geoid model’ is easier to explain for the user community, why this term was preferred.

The first geoid model to be released with RH 2000 was SWEN05_RH2000 (formerly known as SWEN05LR) (Svensson et al., 2006).

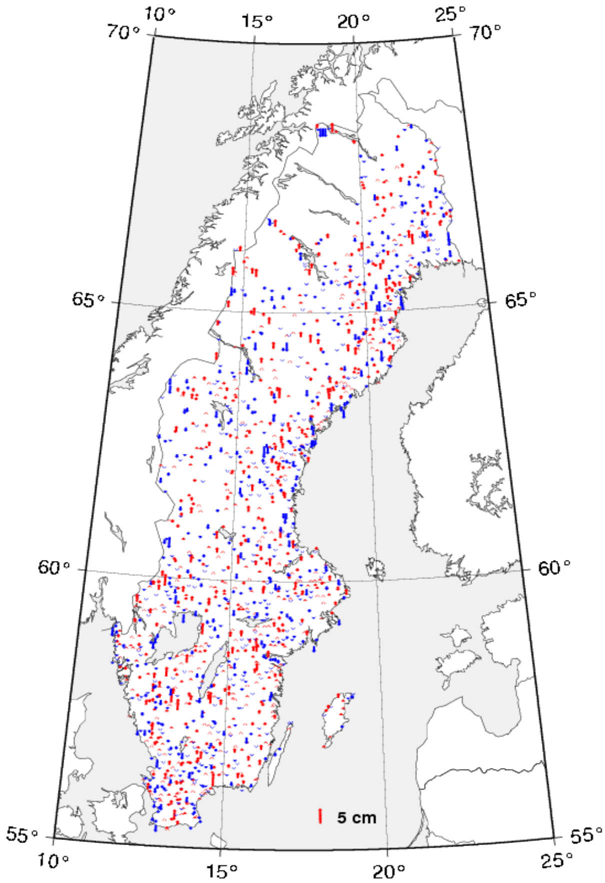

***Figure 4**: GNSS/levelling residuals for SWEN08_RH2000. (Ågren, 2009)*

In 2009, an updated geoid model, SWEN08_RH2000, was released (Ågren, 2009). The model is based on the gravimetric model KTH08 (Sjöberg 2003; Ågren et al., 2008), which was fitted to 1570 high quality GNSS/levelling observations. A land uplift correction was applied, due to the different reference epochs of KTH08, RH 2000 and SWEREF 99. Then a residual correction surface was applied, to further reduce the uncertainty of the model.

SWEN08_RH2000 was evaluated using e.g. cross-validation, resulting in an estimated standard uncertainty of approximately 10-15 mm for the whole country, except for the highest north-western mountains. The uncertainty in this area is dependent on the KTH08 gravimetric model, since there are no GNSS/levelling observations available. A rough estimate of the standard uncertainty in the mountains and at sea would be no better than 5-10 cm.

3.4 Adaptation of SWEREF 99 to absolute antenna models

SWEREF 99 was determined using relative antenna models according to the igs_01.atx antenna table, but antenna calibration methods have been refined – resulting in absolute antenna models – since the establishment of SWEREF 99.

The new version of the network RTK software that was implemented at SWEPOS during the autumn 2011, could only handle absolute antenna models, why it was a good opportunity to introduce absolute antenna models for use with SWEREF 99. In connection to this, the SWEREF 99 coordinates had to be updated to be consistent with the igs08.atx absolute antenna models.

Based on IGS (International GNSS Service) stations, corrections for antenna model changes have been computed, from igs_01.atx relative antenna models to igs05.atx absolute antenna models (Ferland & Bourassa, 2006; Ferland, 2006), and from igs05.atx to the updated absolute antenna models in igs08.atx (IGS, 2011).

Jivall (2012) found that the change from relative antenna models (igs_01.atx) to absolute antenna models (igs05.atx) would not have any significant impact on the SWEREF 99 definition, because the relation between Dorne Margolin choke-ring antennas – the reference antenna used for relative antenna calibration – and the Dorne Margolin copies, used at many SWEPOS stations, is practically unchanged. Tests on a Nordic campaign verified this assumption. The campaign was processed with both antenna tables. RMS of the differences were on the 1 mm level for all components and the solution with igs05.atx antenna models proved to fit as good to SWEREF 99 as the solution processed with igs_01.atx.

The antenna models for the Dorne Margolin antennas, as well as copies of them, were updated between igs05.atx and igs08.atx, implying that the SWEREF 99 coordinates were not fully consistent with igs08.atx. The IGS (2011) latitude dependent corrections were tested, and it was found that they were representative for the SWEPOS network and the SWEREF 99 definition.

CORS stations with Dorne Margolin choke-ring antennas and NONE or OSOD radomes – for which the antenna model is the same in igs05.atx and igs08.atx – kept their original SWEREF 99 coordinates.

Stations with Dorne Margolin choke-ring antennas NONE or OSOD radomes – for which the antenna model is different in igs05.atx and igs08.atx – had their SWEREF 99 coordinates updated with the IGS latitude and antenna type dependent corrections.

Some Finnish CORS stations had SNOW radomes, where the specific antenna/radome combinations were treated differently in igs_01.atx compared to igs05.atx and igs08.atx. Therefore the correction was done in two steps. First, the latitude and antenna type dependent correction between igs05.atx and igs08.atx was done, and then translations in three dimensions were applied to correct for the difference between relative and absolute antenna models.

Updated SWEREF 99 coordinates for stations with other antennas than Dorne Margolin choke-ring antennas and NONE/OSOD radomes, were determined from the updated coordinates of the stations mentioned above. The corrections for Dorne Margolin choke-ring antennas and NONE/OSOD radomes were up to 5 mm and for other antenna/radome combinations up to 15 mm in height.

3.5 Consolidation points for SWEREF 99

Since SWEREF 99 is realized through the CORS network, it is therefore dependent on the CORS network and its positioning services, like network RTK. All modifications of the station equipment or software, as well as the development of the GNSS systems, can in the end affect the coordinates. In order to have these alterations under control, so-called consolidation points have been introduced. (Engberg et al., 2010)

The consolidation points are marked in bedrock and they are all supposed to be well suited for GNSS measurements. All of the points should preferably also have RH 2000 heights from levelling. There are about 300 points in total. Following a yearly programme, around 50 points are re-measured every year, i.e. each point will be re-measured every six years.

At every re-measurement the point is occupied for two 24-hour sessions, including re-setup of the tripod between sessions, and coordinates are computed using reference station data from the fundamental SWEPOS stations.

The same type of antennas as on SWEPOS fundamental stations, i.e. Dorne Margolin choke-ring antennas, are used. In order to minimize centering errors, a new setup is made between the sessions and a special rotating centering device is used. The data are processed station by station connected to the 6-8 closest SWEPOS fundamental stations using the Bernese GNSS Software using a similar processing strategy as for the original SWEREF 99 campaign. If the point is close to the border, also foreign CORS that were included in the original SWEREF 99 campaign are included in the processing. The two sessions are compared and combined and finally after reduction for the internal deformations using the velocity model NKG_RF03vel, the combined solution is fitted to SWEREF 99 with a three-dimensional Helmert transformation.

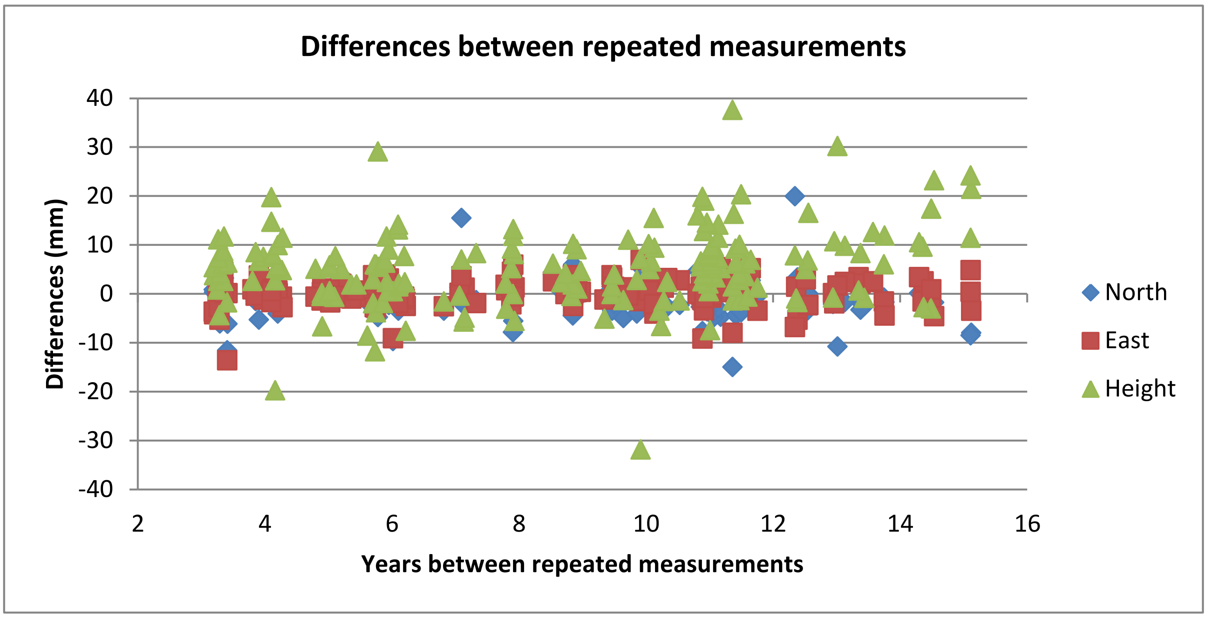

Figure 5*: Differences between repeated measurements of consolidation points, as a function of time separation between the measurements. Data from 1996-2011.*

The first measurements with the present observation strategy were performed in 1996. The measurements between 1996 and 2011 have been processed using a similar strategy. The same antenna table igs_01.atx was used but some minor changes of e.g. elevation cut-off and troposphere modelling were introduced meanwhile. Figure 5 shows the differences between repeated measurements during this time period as a function of the time separation between the repeated measurements. RMS for the differences are 3-4 mm for the horizontal components and 10 mm in height, which could be interpreted as a standard uncertainty of 2-3 mm in the horizontal components and 7 mm in height for a single measurement. Interesting to note is that during this time period no degradation of the repeatability is seen, which proves that our concept for SWEREF 99 works so far, i.e. we are after 15 years able to determine coordinates in SWEREF 99 with approximately the same uncertainty.

However it should be noted that we have lately experienced that the alignment to SWEREF 99 has degraded especially in the north, close to the land uplift maximum, which indicates that we soon would need an updated velocity model.

Further analysis of the consolidation points using a homogenous processing strategy is on-going with both the Bernese GNSS Software and GAMIT-GLOBK.

3.6 Reference frame handling in SWEPOS' Positioning services

SWEPOS offers two national high precision services; SWEPOS Network RTK service and SWEPOS Post-processing service as well as local/regional densifications of these services mainly for infrastructure projects, so called Project adapted services.

SWEPOS Network RTK service is utilizing Trimble Pivot Platform GNSS Infrastructure Software (Trimble, 2016), operated in virtual reference station mode. SWEREF 99 coordinates have been entered as known coordinates of the reference stations. These coordinates are then transformed to the present ITRF, where they will be constrained in the modelling of error sources. The transformation is performed with standard EUREF transformations combined with velocities from the NKG_RF03vel model. In this way the constrained coordinates will agree with the present situation and not introduce systematics into the estimated corrections from the error modelling, as would have been the case if the internal deformations not had been taken into account. It should be mentioned that it is possible in the latest version (3.8) of Trimble Pivot Platform to use so called dynamic station coordinates for the error modelling (Blatt & Erencia-Guerrero, 2015). This reduces the need for using a velocity model for internal defomations in the software.

SWEPOS Post-processing services are based on the Bernese GNSS Software version 5.2. The calculations are performed in the present ITRF and in the end the solution, including the point to be determined and the SWEPOS stations, is reduced to epoch 1999.5 using the velocity model NKG_RF03vel and finally fitted to the SWEREF 99 coordinates of the SWEPOS stations. In the national Post-processing service the fit is made on five SWEPOS stations using a three-dimensional Helmert transformation solving for translations and rotations. In the Project adapted post-processing service the fit is made on at least two stations by solving just for translations.

3.7 Maintenance of RH 2000

Unlike SWEREF 99, RH 2000 is considered a static reference frame realized by a passive network. The deformations caused by the land uplift could be neglected when measuring to close-by points. Therefore it is important that a dense network of RH 2000 remains, i.e. the levelling network needs to be updated on a regular basis.

The update of the third precise levelling network started in 1994. The plan was to invent the points – and replace all points that were found to be destroyed – every twelve years in the expansive parts of the country and every 25 years in the more sparsely populated areas. For different reasons, it was not possible to follow this schedule. In 2009 the principles for updating of the network were revised, to minimize the costs.

Since then only a selection of the destroyed benchmarks are replaced, following the criteria below (Ågren & Engberg, 2010), implying that certain benchmarks are of higher value than others:

- All benchmarks are replaced in municipalities where the local authorities have not done their transition from the old local height systems to RH 2000.
- Benchmarks that are demarcated in bedrock are replaced if the distance between the remaining benchmarks otherwise would be more than 15 levelling sections (c. 15 km).
- A benchmark is replaced if it was the only remaining benchmark demarcated in bedrock within two sections from a nodal point.
- Nodal point benchmarks are replaced if there are no benchmarks demarcated in bedrock within two sections.
- All benchmarks are replaced if six or more successive benchmarks along a levelling line are destroyed.
- If a benchmark has been replaced and also the adjacent points are destroyed, these should be replaced.

If the network in the sparsely populated areas should be updated or not, will be subject of a discussion within the next few years.

Land uplift correction is not applied when individual benchmarks are replaced, due to the relatively short levelling distances. However, correction for land uplift is applied at the adjustment of new levellings, when extensions or more large-scale densifications of the original network are done.

4. DISCUSSION AND FUTURE DEVELOPMENTS

The motivation for choosing a reference frame strategy where coordinates and heights are in principle fixed can be summarised in the following way:

- The user community is used to "static coordinates" and would prefer to keep it that way.
- Dynamic or semi-dynamic reference frames on a national level did not really come into question at the time of establishment of SWEREF 99 and RH 2000, i.e. the late 1990's and the early 2000's. If we were to establish a new reference frame today, we would probably come to the same decision regarding system definition and strategy for the reference frame management.
- We don't want to have to introduce a new reference frame – including the transition process for production, exchange and consumption of geodata – when new velocity models are developed. We have spent almost 15 years introducing the reference frames on national, regional and local level and now we have made substantial progress in the transition process from the old local systems.

As mentioned in section 3.5 the existing velocity models – horizontal as well as vertical – have been sufficient until recently. The more evident need of updated velocity models did not arise until recently. The demands on the velocity models will increase with time. Time will however also give us more observations and possibilities to develop better models. Hence it is logical to update the velocity model when a better model gets available and not include the velocity model in the reference frame definition.

4.1 Future velocity models

Work is going on within the NKG with both empirical land uplift modelling and geophysical GIA modelling. A new empirical land uplift model is planned to be released/published during 2016. The new model will be based on longer GNSS time series and a more refined GIA model, also developed within the NKG cooperation.

Also the horizontal components will be considered both in the GIA modelling and the empirical modelling.

4.2 Future geoid models

Work is going on within the NKG also regarding geoid modelling. A new geoid model is planned to be published during 2016, aiming at the 10 mm uncertainty level. The very challenging long term ambition, is to develop and publish a geoid model at the 5 mm uncertainty level by 2020 or somewhat later.

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BIOGRAPHICAL NOTES

Ms. Christina Kempe

Ms. Kempe holds a B.Sc. in Mapping and Surveying from the University of Gävle, Sweden. She is since year 2000 working at the Geodetic Infrastructure Department of Lantmäteriet, the Swedish mapping, cadastral and land registration authority, mainly with reference frame and co-ordinate system issues. For the past few years she has been supporting the municipalities in their transition to the new national reference frames SWEREF 99 and RH 2000. She is also involved in GNSS analysis, mainly for monitoring of the CORS network.
Ms. Kempe is a member of the Swedish Mapping and Surveying Association.

Ms. Lotti Jivall
Ms. Jivall holds an M.Sc. in Land Surveying from the Royal Institute of Technology in Stockholm, Sweden. She is since year 1987 working at the Geodetic Infrastructure Department of Lantmäteriet, the Swedish mapping, cadastral and land registration authority, mainly with GNSS analysis and reference frame issues. She has established the Swedish ETRS89 realization, SWEREF 99, as well as number of other ETRS89 realizations in Europe.

Dr. Martin Lidberg
Dr. Lidberg is the Head of the Reference frame section at the Geodetic Infrastructure Department at Lantmäteriet, the Swedish mapping, cadastral and land registration authority. He has a M.Sc in Surveying and mapping from the Royal Institute of Technology (Stockholm, Sweden) in 1988, and got his PhD from Chalmers University of Technology (Gothenburg, Sweden) in 2007. He has been working at Lantmäteriet since 1988. Martin is also a member of the EUREF Technical Working Group.

Mr. Mikael Lilje
Mr. Lilje is the Head of the Geodetic Infrastructure Department at Lantmäteriet, the Swedish mapping, cadastral and land registration authority. He graduated with a M.Sc. with emphasis on geodesy and photogrammetry from the Royal Institute of Technology (Stockholm, Sweden) in 1993. He has been working at Lantmäteriet since 1994, mainly at the Geodetic Infrastructure Department. Mikael is the past chair of FIG Commission 5, has been involved in FIG since 1998 and is currently the chair of the FIG Task Force on Commission Structure.

CONTACTS

Ms. Christina Kempe
Lantmäteriet
Land and Geographic Information Services – Geodetic Infrastructure Department
SE-801 82 Gävle
SWEDEN
Tel. +46 26 633856
Fax +46 26 610676
Email: christina.kempe@lm.se
Web site: www.lantmateriet.se/geodesi