The New Swedish Height System RH 2000 and Geoid Model SWEN 05LR

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Key words: height system, levelling, postglacial land uplift, geoid

SUMMARY

Sweden released the new national height system RH 2000 in 2005. It is based on 25 years of levelling using the motorised levelling technique. The system is defined to agree with the European Vertical Reference System (EVRS), implying for instance that normal heights are utilised. Due to the postglacial rebound, it is important that the observations are reduced to a common reference epoch. For this purpose, the new land uplift model NKG2005LU was constructed as a combination of the mathematical (empirical) model of Vestøl (2005) and the geophysical model of Lambeck, Smither and Ekman (1998). The reference epoch was chosen to 2000.0. The computation was made in collaboration with the other Nordic countries under the umbrella of the Nordic Geodetic Commission (NKG) and in co-operation with the IAG Reference Frame Sub Commission for Europe (EUREF). Data from the Netherlands, Northern Germany, Poland, Latvia, Lithuania, Estonia, Finland, Sweden, Norway and Denmark were incorporated into the adjustment, forming what has been termed the Baltic Levelling Ring. As the new height system fits very well with the systems of our neighbouring countries, the sharing of height information and cross-boundary work become easy tasks.

To facilitate height determination by GPS, the geoid model SWEN 05LR was introduced in connection with RH 2000. It is based on the Nordic geoid model NKG 2004, which has been fitted to a large number of high quality GPS/levelling geoid heights. It also includes a long wavelength model of the remaining residuals. The result is a geoid model with an accuracy of a few centimetres in most parts of Sweden.

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1. INTRODUCTION

In 2005 Sweden introduced the new national height system RH 2000. It is the result of the third precise levelling of Sweden, in which the technique of motorised levelling has been utilised. To obtain heights agreeing as closely as possible with the other European countries, the system was defined to be the Swedish realisation of the European Vertical Reference System (EVRS). It should be noticed, though, that it has so far not been defined on the European level how the phenomena of postglacial rebound should be treated. To reduce the observations to a common reference epoch, the postglacial land uplift model NKG2005LU was constructed in Nordic collaboration under the umbrella of the Nordic Geodetic Commission (NKG). The RH 2000 adjustment was made in co-operation with NKG and EUREF (IAG Reference Frame Sub Commission for Europe) and included observations from the whole Baltic Levelling Ring, which consists of the levellings from all the countries around the Baltic Sea as well as Northern Germany and the Netherlands. To facilitate for GPS users, a new geoid model, SWEN 05LR, was introduced in connection with the release of the new height system.

It is the main purpose of this paper to present RH 2000 and a number of related topics. First, the third precise levelling is introduced. After that, the system definition and the construction of the postglacial rebound model NKG2005LU is described in some detail. The geoid model SWEN 05LR is then presented. The paper ends with a few words regarding the practical implementation of RH 2000 in Sweden.

2. THE THIRD PRECISE LEVELLING OF SWEDEN

2.1 Introduction

The fieldwork of the third precise levelling of Sweden started in 1979 and the last line in the network was observed in 2001. To understand why a new levelling was needed, it is illustrative to consider the earlier precise levellings; see Fig. 1. The first one was performed in 1886-1905. Due to the reasons that the network was not sufficiently dense, that the coverage of the country was poor and that the quality of the heights was low, a second precise levelling was performed from 1951 to 1967. The reasons to start yet another levelling (the third) were mainly the same, even though the demands from the users for better coverage and accessibility were even stronger this time. The second levelling was mainly located along railroads, which made the benchmarks hard to reach. In course of time many benchmarks had also been destroyed. The aim of new third precise levelling was therefore to create a network covering the whole country, dense enough to allow all the local users to connect their measurements to easy accessible benchmarks. Another aim was to achieve a better estimation of the land uplift by comparing the new levelling with the old ones (Eriksson et al. 2002).

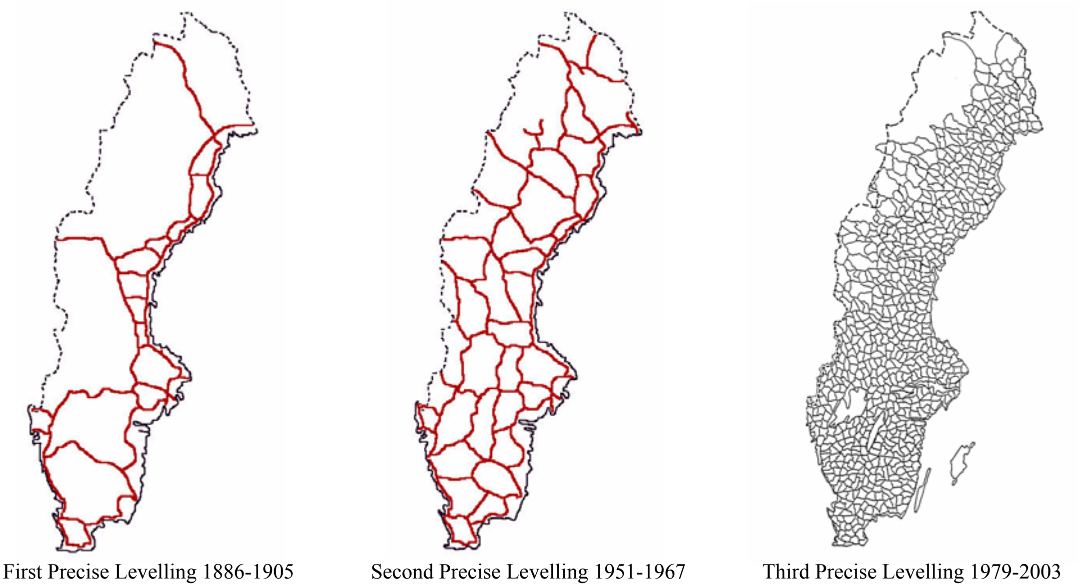

First Precise Levelling 1886-1905 Second Precise Levelling 1951-1967 Third Precise Levelling 1979-2003

Figure 1: The three precise levellings of Sweden

The network of the third precise levelling is dense and homogeneous at the same time as all levelling was carried out with same technique utilising the same equipment. The benchmarks should thus be very accessible to the users and the quality of the resulting RH 2000 heights should be high and homogeneous.

2.2 The RH 2000 height network

The network consists of approximately 50 000 km double run levelling and the number of benchmarks is 50 800. The distance between them is about 1 km. The network covers the whole country in closed loops, with a circumference of approximately 120 km, except for the mountain areas to the North-West where the roads are very few. This makes it impossible to achieve the same density there; see Fig. 1. However, since the population is also very sparse in these areas, this is not too critical. The lines are connected to the levelling lines of our neighbouring countries, which results in closed loops along the borders. This also makes it possible to extend the network to the whole Baltic Levelling Ring; cf. Sect. 3. The network was planned in co-operation with the local users in order to increase the utility of the points for the connection of local measurements.

2.3 The levelling observations

The observations were carried out by means of the motorised levelling technique using one instrument car and two rod cars. The instrument is a Zeiss Jena NI002 with a 360 degree rotating eyepiece and a reversible pendulum giving a quasi-absolute horizon. The rods are 3.5 m invar staffs with double scales. A separate 3.0 m invar rod is used for the connection to the benchmarks. The average sight length is approximately 35 meters (50 meters allowed). To make it possible to determine the land uplift, accessible points from the former precise levellings were connected to the network. The rejection limit was $2\sqrt{L}$ mm (L in km) during the whole project, which corresponds to a 2-sigma limit. If the measurements of a section differed more than this limit, then the section was relevelled. About 7 % of all sections have been remeasured for this reason. The whole production line, from the observations to the archive, is digital. All observations are stored in data loggers together with other information. About 50 different items are saved for each section. Today the levelling database contains more than 120 000 single run sections. In addition to the levelling database, a benchmark database is used that contains information regarding the benchmarks, such as type of marker, benchmark number, description of the location, a digital sketch, height and other information needed to find the point, to identify and use it. All this information can be printed out on a form. A digital map can also be printed, showing all benchmarks and their numbers located on a specific map sheet.

3. THE BALTIC LEVELLING RING

A major part of the processing of the precise levellings of Sweden, Finland and Norway was made as a Nordic co-operation under the auspices of NKG. Denmark also contributed actively to the task, even though the Danish height system DVR 90 had already been finalised at the time. To be able to connect to the Normaal Amsterdams Peil (NAP), which is the traditional zero level for the United European Levelling Network (UELN), and to be able to determine the relations to our neighbouring countries, it was decided to extend the Nordic network with the precise levellings from the Baltic States, Poland, Northern Germany and the Netherlands. The non-Nordic data was provided by EUREF from the UELN-database.

The whole network, which has been named the Baltic Levelling Ring, is illustrated in Fig. 2. Unfortunately, it has not been possible to close the ring with levelling observations around the Gulf of Finland. However, by means of other information (sea surface topography or GPS in combination with a geoid model), closing errors may still be computed. This amounts to a valuable check of the adjustment. It should be noticed, though, that only levelling observations are included in the final adjustment. As can be seen in Fig. 2, the Baltic Levelling Ring extends over a quite large area. To be able to reduce all observations for the postglacial land uplift, the applied model should naturally cover the same area. This should be kept in mind in what follows.

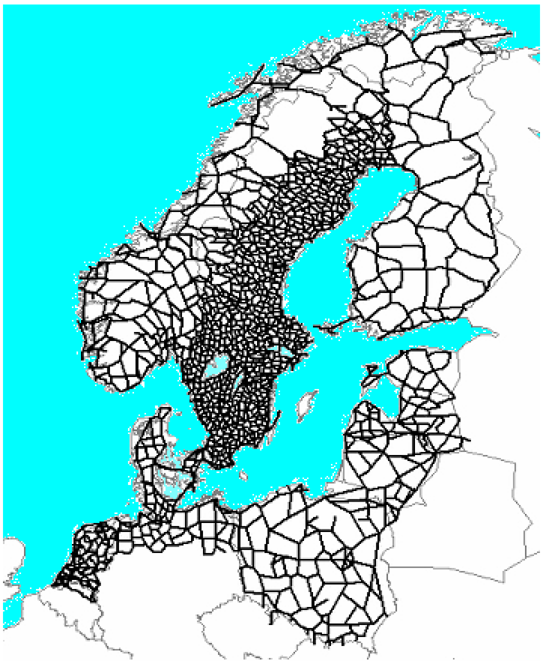


Figure 2: The Baltic Levelling Ring.

4. SYSTEM DEFINITION FOR RH 2000

As mentioned in the last section, much of the work to process the Baltic Levelling Ring was made as a Nordic co-operation within the NKG. This also includes the choice of system definition (datum) and the construction of a land uplift model. However, due to the tough time limitations to finalise RH 2000, the work on system definition and land uplift model had to be finished by Sweden in January/February 2005 (Ågren and Svensson 2006d). At that time, most aspects of the definition had already been discussed on the Nordic level, for instance the common reference epoch for the postglacial land uplift.

Now, it was first decided that RH 2000 should be defined as the Swedish realisation of the European Vertical Reference System (EVRS). The main reason for this was to arrive at a system that agrees as well as possible with other European systems. From this decision it follows that (EUREF-homepage; Ihde and Augath 2001):

- The **zero level** is given by the geopotential number from the latest official UELN-solution (EVRF 2000) for the Normaal Amsterdam Peil (NAP). It is true that NAP is not strictly a part of the definition of the EVRS, but at the time it was the only available alternative to realise EVRS (as for EVRF 2000).
- **Normal heights** are utilised.
- The zero system is utilised for the **permanent tide**.

One problem with the present EVRS definition is that no advice is given of how the postglacial land uplift should be treated. This means that these matters had to be taken care of at the Nordic level. Since the postglacial rebound is a very significant phenomena (see the next section), the system definition for RH 2000 should specify how the land uplift is handled. The RH 2000 definition therefore includes the following items:

- The **reference epoch** for the reduction of postglacial rebound is 2000.0. This was decided at the Nordic level within the NKG.
- The **postglacial land uplift model** is NKG2005LU. The construction of this model is described in the next section.

It should be pointed out that the RH 2000 definition was applied for the adjustment of the whole Baltic Levelling Ring, even though RH 2000 is strictly only a Swedish system.

5. POSTGLACIAL REBOUND MODEL

The Nordic area (Fennoscandia) still experiences postglacial rebound after the melting of the ice covering Northern Europe some 10 000 years ago. The maximum uplift is approximately 1 cm per year; see Fig. 3. This means that in projects with geodetic measurements conducted over longer time periods in high accuracy applications, the phenomena must be taken into account. To correct all measurements to a suitable reference epoch (see the last section), a model that describes the uplift is needed.

As mentioned above, the work to construct a land uplift model has been conducted in Nordic collaboration. The first part of this work was to evaluate the existing land uplift models to see to what extent they were suitable for the task. After that, it was decided to combine them to reach the best possible result. Below, the three main models evaluated are first described. After that, the combination procedure leading to the final uplift model is summarised. It should be pointed out that more models than the ones presented here have been considered, but only the three main candidates are treated here.

5.1 The model of Ekman (1996)

The first model is the one by Ekman (1996), which has been constructed using repeated levelling and the apparent uplift estimated from long time series at 58 tide gauges. The main problems with this model are that it only uses the first and second precise levellings in Sweden, that it is based on no information in the interior parts of Sweden as well as Norway and that it does not cover the whole area of the Baltic Levelling Ring. In addition, no uplift values from GPS were available to Ekman (ibid.). Due to these reasons, it was concluded that this model is not suitable for the task.

5.2 The geophysical model of Lambeck, Smither and Ekman (1998)

Another alternative is to use a geophysical model, which consists of a physical model of the lithosphere, the mantle and the ice sheet. One advantage with this kind of model is that it may provide a geophysically meaningful interpolation and extrapolation of the uplift phenomena. For instance, from the fact that the lithosphere is comparatively rigid, it follows that the land uplift model should be smooth. The lithosphere can sustain loads of smaller dimension.

Now, the geophysical model of Lambeck, Smither and Ekman (1998) was singled out as the best geophysical model available. This model has been tuned to the apparent uplift in the tide gauges referred to in the last subsection (Ekman 1996), some lake level observations and ancient shore lines. The model was only available as a digital image from a publication, meaning that we had to digitise it for the purpose. The digitised version (NKG) is here referred to as Lambeck's model. The evaluation of Lambeck's model was made by studying the residuals in the tide gauges as well as at permanent GPS stations, converted to apparent land uplift using the Eustatic sea level rise 1.32 mm/year and 6% geoid rise (Vestøl 2005). The result shows clearly that the model is very biased in the interior parts of Sweden. The errors are systematically as large as 1-1.5 mm/year. Mainly due to this reason, it was decided that the geophysical model of Lambeck et al. (1998) could not be used. Since it was out of the question to compute a new geophysical model, it was then decided to go for a mathematical (or empirical) model or to modify Lambeck's model for those areas in which better information is available.

5.3 Vestøl's Mathematical Model

A mathematical (or empirical) uplift model consists of a mathematically defined surface that has been constructed to fit the available land uplift observations in some suitable way. In 2005, one such model had been developed by Olav Vestøl from the Norwegian Mapping Authority. Since then Vestøl has continued to modify his model, but here only the model available in January 2005 (available at the deadline for RH 2000) is treated. It is presented in Vestøl (2005). The land uplift observations used by Vestøl stem from the tide gauges, the permanent GPS stations and the repeated levellings in Finland, Norway and Sweden. By means of least squares collocation with unknown parameters using a polynomial trend surface of degree 5, the land uplift is estimated in the observation points. From these point uplift values, the land uplift is estimated in a grid using a simple gridding algorithm (mean of four observations, one in each search quadrant if closer than 120 km).

The model agrees well with the observations but is not defined for the whole BLR, which is a drawback. Few observations outside the Nordic countries are included and the simple gridding algorithm leads to strange "staircase cylinders" at the outskirts of the model. Furthermore, the model looks a little too rough with zigzag contour lines). Consequently, some smoothing might be motivated. One problem with a mathematical land uplift model is that it is not evident how the algorithm should be "tuned".

5.4 Combination of Vestøl's and Lambeck's Models (NKG2005LU)

One clear advantage of Lambeck's model is that it covers the whole Baltic Levelling Ring area in a reasonably realistic way. Vestøl's model does not. On the other hand, Vestøl's model fits much better with the observations over the Nordic countries compared to Lambeck's model. Therefore, a combination of the two seems like the best possible choice to cover the whole area, all the way down to NAP.

Many different ways to optimise the combination have been explored, which will not be described in this paper. Interested readers can study Ågren and Svensson (2006c and 2006d). The final model, which was originally called RH 2000 LU (Ågren and Svensson 2006d), is basically a smoothed version of the model of Vestøl (2005) in the central (Nordic) parts of the uplift area. Outside this, a smooth transition to Lambeck's model is accomplished. The RH 2000 LU model has later received a more official status within the NKG and has been named NKG2005LU. The model, which is illustrated in Figure 4, was applied in the RH 2000 adjustment of the Baltic Levelling Ring.

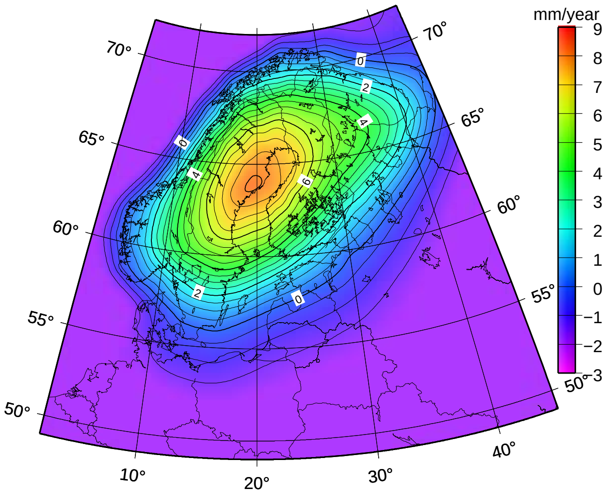


Figure 3. Apparent land uplift from the NKG2005LU model. Unit: mm/year.

6. ADJUSTMENT OF RH 2000

All levelling data from the whole Baltic Levelling Ring was included in the final adjustment of RH 2000. It should be stressed that *only* levelling observations were utilised. First, one least squares adjustment was made of the geopotential differences between a total of 7 400 nodal points, of which 5132 are Swedish. The national data sets in BLR were given the weights determined by Karsten Engsager on behalf of NKG. The Swedish aposteriori standard error of unit weight is approximately 1 mm/√km. The estimated standard errors with respect to the NAP are illustrated in Fig. 4, which also contains the standard errors relative to Gävle, situated in the central part of Sweden.

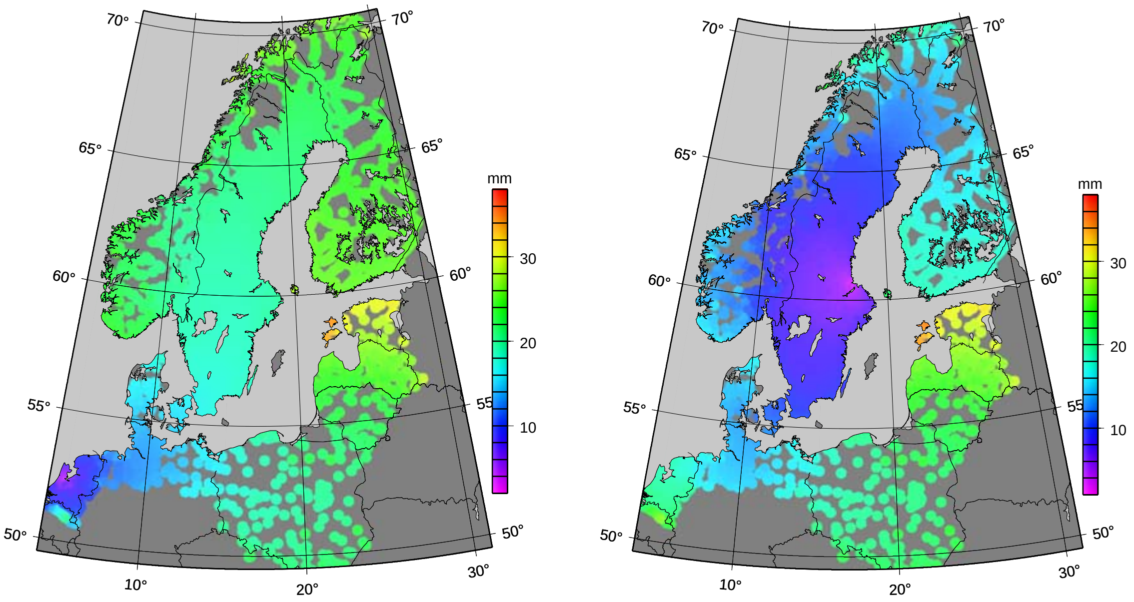


Figure 4: Estimated standard errors relative to NAP (left) and Gävle (right). Unit: mm.

The result from the first adjustment, which is geopotential numbers at the nodal benchmarks, was then used as known values in the adjustment of all other benchmarks. In total, about 50 000 points have been determined in RH 2000. In the final step, the geopotential numbers were converted to normal heights.

A comparison between the new system RH 2000 and the old RH 70 (epoch 1970) shows that the difference in heights varies between 7 and 32 cm, which can mainly be explained by the different land uplift epochs and by the different permanent tide systems; see Ågren and Svensson (2006d) for more details and for comparisons with other height systems.

7. THE GEOID MODEL SWEN 05LR

7.1 **Introduction**

The geoid model SWEN 05LR was released in connection with the new height system. It is used to relate normal heights in RH 2000 to GPS heights above the ellipsoid in the Swedish national three dimensional system SWEREF 99 (Jivall 2001). It should be pointed out that the word *geoid model* is here used in a rather loose sense. First, as normal heights are utilised in RH 2000, it would strictly be more correct to speak of a *quasigeoid model*. Second, since other effects are included in the model, such as a correction for different permanent tide systems, it would perhaps be even better to prefer *height correction model* or some similar phrase. However, it is our experience that the word *geoid model* is easier to explain for beginners. This is the main reason for nevertheless preferring this term.

7.2 GPS/levelling observations

The geoid model is constructed by fitting the gravimetric quasigeoid model NKG 2004 to 1178 GPS/levelling height anomalies in the reference systems SWEREF 99 and RH 2000. The stations are either permanent GPS stations (SWEPOS™) or benchmarks in the third precise levelling of Sweden. In a few cases an eccentric GPS point is used very close to the benchmark. The stations are divided into three groups depending on the method utilised to determine the GPS height in SWEREF 99; see Table 1.

Table 1. The GPS/Levelling observations and their approximate standard errors.

Data set	#	Short description	Appr. standard errors (mm)		
			GPS height	Normal height	Height anomaly
SWEPOS	20	Permanent GPS stations whose coordinates defines SWEREF 99 (Jivall 2001)	5-10	5-10	7-14
SWEREF	88	Determined relative to SWEPOS using 48 hours of obs, DM T antennas and the Bernese software	10-20	5-10	11-22
RIX 95	1070	Densification of the above stations using static GPS with 0.5-1.0 hours of obs. per session. Not yet covering the whole of Sweden, mainly missing mountainous areas. Network adjustment	15-30	5-10	16-32

To eliminate as much of the systematic effects as possible, permanent tide and land uplift corrections are applied to the GPS/levelling observations. Since the epochs for RH 2000 and SWEREF 99 only differ by 0.5 years, the land uplift correction is very small. In any case, the land uplift model is NKG2005LU, which was described in Section 5 (Ågren 2006a).

7.3 The NKG 2004 quasigeoid model

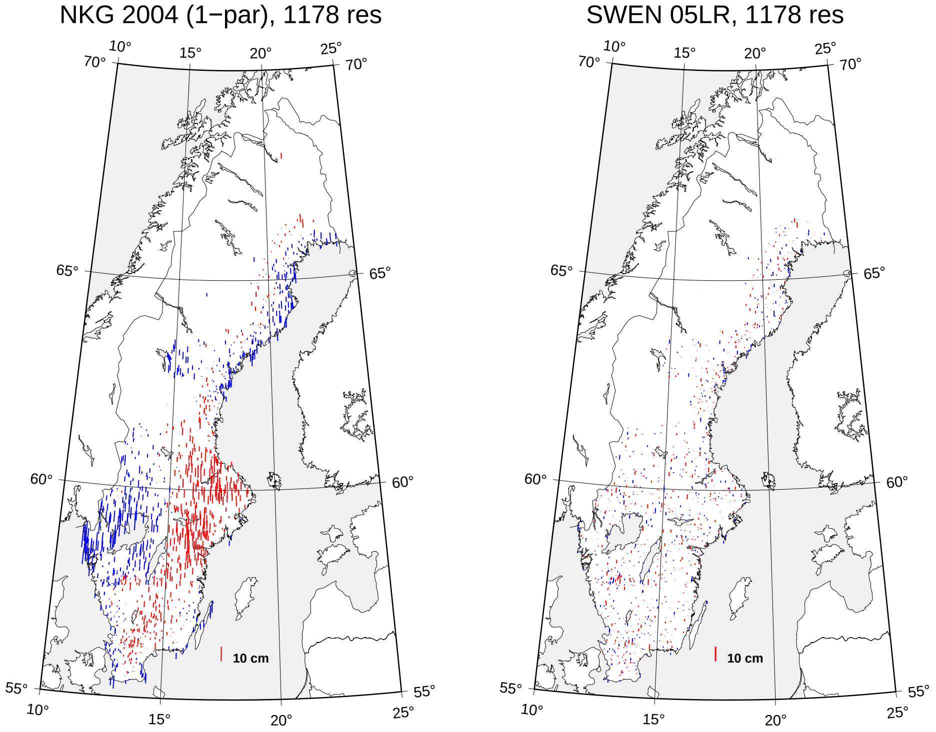
The Nordic gravimetric model NKG 2004 was chosen since it was judged to be the best gravimetric model available for Sweden in 2005. It has been computed by the remove-compute-restore method using a Wong and Gore type of Stokes' kernel and the RTM reduction. The applied Global Geopotential Model (GGM) is a combination of the GRACE model GGM02S and EGM 96 (Forsberg 2004).

Statistics for the GPS/levelling residuals after estimating a shift (1-par. model) to NKG 2004 are presented in Table 2.

Table 2. Statistics for the GPS/levelling residuals after a 1-parameter fit. The NKG 2004 model with land uplift and permanent tide corrections. Unit: mm.

GPS/Levelling data	#	Min	Max	Mean	StdDev
SWEPOS	20	-58	62	0	31
SWEREF	88	-103	75	0	35
RIX 95	1070	-151	96	0	37
SWEPOS and SWEREF	108	-102	76	0	34
All	1178	-151	96	0	37

The 1178 residuals are plotted in the left part of Fig. 4. It can be seen that they show a rather systematic behaviour. It should thus be possible to improve the gravimetric model by adding an interpolated residual surface.


NKG 2004 (1−par), 1178 res

SWEN 05LR, 1178 res

Figure 4: GPS/levelling residuals for NKG 2004 after a 1-parameter fit (left) and for SWEN 05LR (right).

7.4 Interpolation and extrapolation of the residual surface

The interpolation and extrapolation method should satisfy the following criteria:

1. The residual surface should behave well outside the GPS/levelling observations, which means that it should approach zero in a smooth way as one moves away from the observations.
2. High frequency GPS errors should not propagate directly into the surface. To counteract this, a comparatively smooth residual surface should be preferred. Exact interpolation is thus to be avoided in case the dense RIX 95 observations are to be utilised; see Table 1.
3. The surface should fit the observations of high quality better, which means that individual weighting should be applied.

Two different interpolation methods have been investigated in depth, namely least squares collocation and inverse distance interpolation (Bjerhammar's method). Mainly due to the third criterion, least squares collocation as implemented in the GRAVSOFT software GEOGRID is preferred (Forsberg 2003). SWEN 05LR is defined as the sum of the mean value shifted NKG 2004 model and the residual surface.

7.5 Residuals of SWEN 05LR

The SWEN 05LR residuals are plotted in the right part of Fig. 4 and statistics is plotted in Table 3. Notice that the residuals are not a good measure of the accuracy of SWEN 05LR. In case an exact interpolation method is chosen, they become identically zero.

Table 3. Statistics for the GPS/levelling residuals of SWEN 05LR (shift 1-par) + residual surface). Unit: mm..

GPS/Levelling data	#	Min	Max	Mean	StdDev
SWEPOS	20	-10	4	-1	4
SWEREF	88	-17	14	-3	8
RIX 95	1070	-42	41	0	11
SWEPOS and SWEREF	108	-17	14	-3	7
All	1178	-42	41	0	11

7.6 Accuracy of SWEN 05LR

Two different methods were used to investigate the accuracy of SWEN 05LR. The first is the so-called cross validation technique: First, one observation is excluded. A height correction model is then computed using the remaining ones. The difference between the excluded observation and the model yields the first cross validation residual. This procedure is repeated for all observations. The cross validation residuals for all GPS/levelling data are very small and varying between -45 mm up to 47 mm with a standard deviation of only 13 mm. It should be noticed, though, that all errors with longer wavelengths do not show up. This means that the technique can only be used to assess the SWEN 05LR accuracy for GPS measurements over shorter distances. The test nevertheless shows that the high-frequency accuracy of SWEN 05LR is high.

The second method was to compare SWEN 05LR with a newly computed gravimetric model that fits considerably better with the GPS/levelling observations. This model has been computed using the Least Squares Modification Method (LSMM) with additive correction (Sjöberg 1991 and 2003). The computation is documented in Ågren et al. (2006b). The comparison shows that the standard error for SWEN 05LR is somewhere around 15 mm inside the RIX 95 area, i.e. the area with dense GPS/levelling observations in Fig. 4. Since both the NKG 2004 and LSMM models have been computed using almost the same gravity data, it can be expected that the SWEN 05LR and LSMM models are correlated. However, since the long wavelengths are taken from different sources and since the high-frequency accuracy is high (shown by cross validation), it is believed that the correlation is limited. The above 15 mm estimate considers that some correlation is present. Outside the RIX 95 area, it seems reasonably to assume that the accuracy is comparable to what is obtained by NKG 2004 and a shift, which corresponds to a standard error of approximately 30–40 mm. The accuracy is very likely worse in the highest mountains.

8. IMPLEMENTATION OF RH 2000

The work with the introduction of RH 2000 among other authorities in Sweden, such as municipalities, is in progress. The situation in Sweden is that the local authorities have their own height systems and most authorities even have several height systems to work with. This situation complicates for instance the exchange of height information and the use of GPS for height determination. Lantmäteriet is acting as an advice board for the local authorities. Currently, approximately 45 of the 290 Swedish municipalities have, in co-operation with Lantmäteriet, started the process of recalculation and analyses of their local networks, with the aim of replacing the local height systems with RH 2000. So far, four municipalities have finalised the replacement for all activities, but the work has yet only started. Lantmäteriet cannot force the local authorities to act, but we can support them with recommendations. In parallel, many local authorities are also looking over the situation with their horizontal co-ordinate systems. We clearly see a trend that most local authorities will change to SWEREF 99 and RH 2000, or at least make sure that they have good transformations between the different systems.

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BIOGRAPHICAL NOTES

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Mr Svensson graduated in 1987 from the Royal Institute of Technology as a land surveyor with emphasis on Geodesy and Photogrammetry. He has been working at Lantmäteriet since 1988 mainly as a research geodesist at both the Geodetic Research Division and the Geodetic Production Division. His main tasks at the moment are associated with the realization of a new height system in Sweden.

Jonas Ågren

Dr Ågren received his Master of Science degree in Geodesy and Photogrammetry at the Royal Institute of Technology in 1994. After that, he worked with GPS processing and reference frames at Lantmäteriet. He then continued his studies and in 2004 he received his PhD in Geodesy, specialised in Physical Geodesy and Geoid Determination. Since then he is working with Geoid Determination, Gravimetry, Height Systems and Geodynamics at Lantmäteriet.

Per-Anders Olsson

Mr Olsson graduated in 2000 from the Royal Institute of Technology as a land surveyor with emphasis on Geodesy and Photogrammetry. His main task is validation and preparation of data for the third precise levelling of Sweden.

Per-Ola Eriksson

Mr Eriksson graduated as a Survey Engineer from the Technical Institute in Härnösand, Sweden in 1966. Since then he has worked at the Geodetic Production Division at Lantmäteriet and its corresponding organisations with the national geodetic networks. He has participated in the development of the motorised levelling technique in Sweden from the early 1970s, and since 1988 he is responsible for the production of the whole precise levelling project in Sweden.

Mikael Lilje

Mr Lilje graduated in 1993 from the Royal Institute of Technology as a land surveyor with emphasis on Geodesy and Photogrammetry. He is working at Lantmäteriet since 1994 with various topics, mainly at the Geodetic Research Division. Currently he is the head of a group working with reference frame and co-ordinate system questions.

Mr Lilje is chair of the Swedish Map and Measuring Technique Society and chair of the FIG Commission 5 Working Group on ”Reference Frame in Practice”. Mr Lilje was also secretary for FIG Commission 5 during the period 1998 – 2002.

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