Geodetic Reference Frames in Presence of Crustal Deformations

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Key words: Geodetic reference frame, crustal deformation, GPS.

SUMMARY

The focus in this presentation is on principles for, and implementation of, long term management of geodetic reference frames under the circumstance of a deforming crust of the earth. Of special importance is the need from the users to have a reference frame where the coordinate values are stable in time. To achieve this, the deformations of the earths crust must be known. For northern Europe, these deformations are dominated by the Fennoscandian Glacial Isostatic Adjustment (GIA) process, where the maximum land uplift is at the 10 mm/yr level.

A recent 3D velocity field derived from more than 4800 days (13 years) of data at more than 80 permanent GPS sites in northern Europe is first presented. The results agree with tide gauge observations and repeated levellings to the 0.5 mm/yr level. Then a geophysical GIA model has been tuned to best fit to the GPS-derived station velocities. The agreement between model and observations is at the sub-mm/yr level. For the purpose of eliminating or reducing the effects of crustal deformations in surveying applications, the GIA model has then been implemented in a transformation scheme, where new observations are translated backwards in time to the epoch of validity for the national reference frame.

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1. INTRODUCTION

Proper maintenance and management of the European reference system, ETRS89, together with its realizations, requires that possible deformations within its area of validity are taken into consideration. To be able to do so, these intraplate deformations (with respect to the Eurasia tectonic plate) need to be known to a certain level. Of interest in this respect is the area affected of the Fennoscandian post glacial rebound phenomenon.

The BIFROST (Baseline Inferences for Fennoscandian Rebound Observations Sea Level and Tectonicas) project was started in 1993. The first primary goal was to establish a new and useful three-dimensional measurement of the movements in the earth crust based on permanent GPS stations, and use these observations to constrain models of the GIA (glacial isostatic adjustment) process in Fennoscandia (Johansson et al. 2002; Milne et al. 2001).

In this study we have re-analyzed all BIFROST data up to November 2006. The extended period allows us to include more recent GPS sites in northern Europe, resulting in a denser sampling of the GIA process (compared to Johansson et al 2002). This is most evident for Norway, but partly also for continental Europe. In addition to ITRF2000, we have aligned our solution to the new ITRF2005 reference frame. The solutions are also compared to an updated GIA model.

2. THE BIFROST GPS NETWORK

The sites included in the analysis presented here are shown in Figure 2-1. A description of the BIFROST GPS network, originally composed of the permanent GPS network of Sweden and Finland, and here improved by also including more sites in Norway, Denmark, and sites in the EUREF Permanent Network (EPN), may be found in Lidberg et al. (2007).

By including stations also outside of the former ice sheet, we include also the subsiding forebulge, and may eventually determine the area where the effects of the GIA process must be taken into account. The additional stations are also needed for reference frame realization when the regional BIFROST analysis is combined with networks from global analysis (see section 3 below).

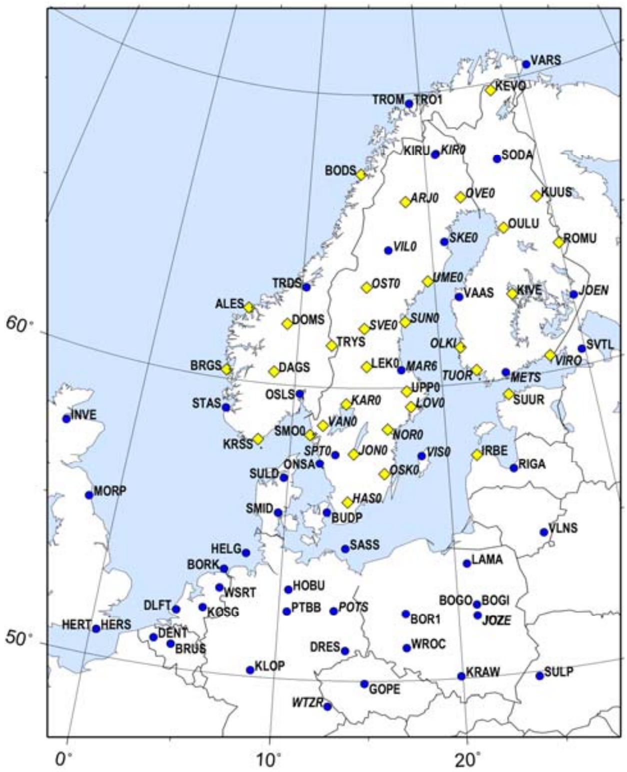


Figure 2-1. The extended BIFROST network. Filled dots mark sites available in the public domain through EPN or IGS. Diamonds mark sites in national densifications.

3. DATA ANALYSIS

3.1 Analysis of GPS data

We have used the GAMIT/GLOBK software package (Herring et al 2006a-c), developed at the Massachusetts Institute of Technology (MIT), Scripps Institution of Oceanography, and Harvard University for analysis of the GPS data. Main characteristics of the GAMIT/GLOBK software are that dual frequency GPS observations from each day are analyzed using GAMIT applying the double differencing approach. The results are computed loosely constrained Cartesian coordinates for stations, satellite orbit parameters, as well as their mutual dependencies. Results from analyzed sub-networks are then combined using GLOBK, which is also used for reference frame realization.

For the GAMIT part of the analysis we have applied an identical strategy as in Lidberg et al. (2007). That is a 10° elevation cut off angle, atmospheric zenith delays where estimated every second hour (piece-wise-linear model) using the Niell mapping functions (Niell 1996) together with daily estimated gradient parameters. Elevation dependent weighting based on a preliminary analysis was applied, and GPS phase ambiguities were estimated to integers as far as possible. Station motion associated with ocean loading and solid Earth tides were modeled, and a priori orbits from the Scripps Orbit and Permanent Array Center (SOPAC), "g-files", were used. In the analysis corrections for antenna phase centre variations (PCV) have been applied according to the models relative to the AOAD/M_T reference antenna models.

In the second step of the processing, GLOBK was used to combine our regional sub networks with analyzed global networks into single day unconstrained solutions. Finally, constraints that represent the reference frame realization was applied by using a set of globally distributed fiducial stations and solving for translations, rotations and a scale factor, as well as a slight adjustment of the satellite orbit parameters. The result comprises stabilized daily station positions, satellite orbit parameters, and earth orientation parameters (EOPs) (Nikolaidis 2002).

3.2 Reference Frame Realization

The purpose here is to derive a 3D velocity field of the deformation of the crust in Fennoscandia dominated by the ongoing GIA process. In order to resolve the slow and small-scale deformation of the region, a terrestrial reference frame (TRF) consistent over the period of analysis is needed. We also would like to avoid perturbations from individual stations as far as possible. The natural choice was therefore to adapt to the International Terrestrial Reference Frame (ITRF) as global constraints. We have thus constrained our solutions to booth the ITRF2000 (Altamimi et al. 2002), as well as to the more recent ITRF2005 (Altamimi et al. 2007) reference frames.

For the velocity solution presented here, we have combined our regional BIFROST analysis with a global analysis comprising 35 selected sites. The daily combined networks have then been stabilized using 23 sites as candidates for reference frame realization. See Figure 3-1.

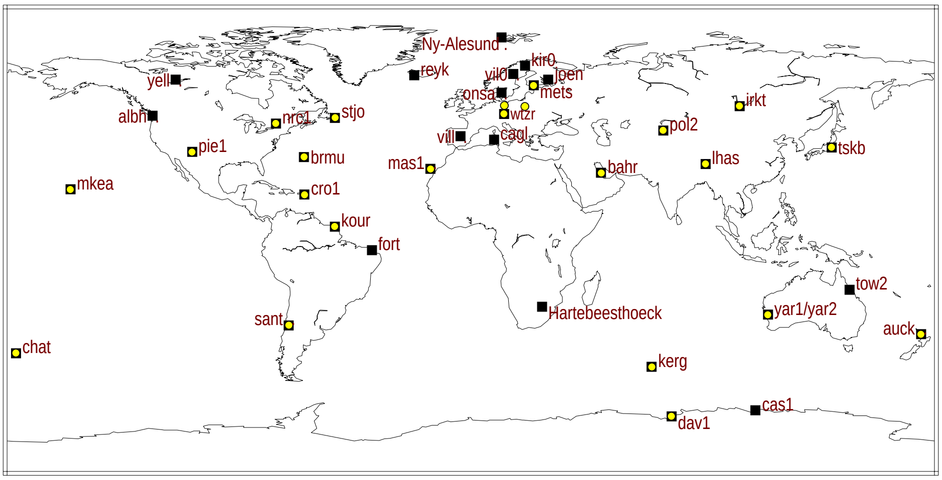


Figure 3-1. Network of 35 sites (black squares) and the 23 sites (light circles) used for reference frame realization.

Thus, we have chosen not to follow the strategy applied in Lidberg et al. [2007a], where the regional BIFROST solution was combined with global analyzed networks made available by

SOPAC. A preliminary analysis, computed using the traditional strategy showed clear non-linear, or bent, shape in the vertical position time series.

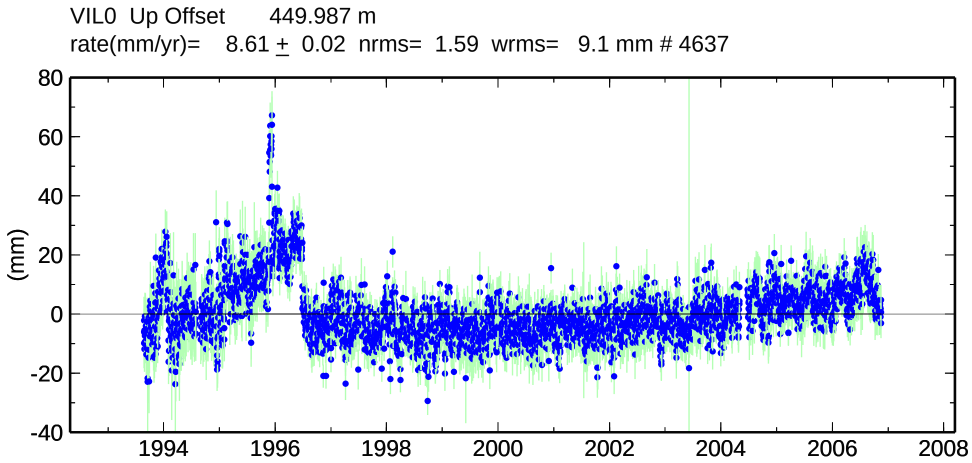


Figure 3-2. De-trended time series plot of daily vertical position estimates from Vilhelmina (VIL0) (64°N) for the complete period of analysis (Aug 1993 to Oct 2006). Here the regional BIFROST analysis has been combined with the global analysis from SOPAC. See text.

Figure 3-2 shows de-trended time series plot of daily position estimates, based on combination of the regional BIFROST analysis with SOPAC products, in ITRF2005 from Vilhelmina (VIL0) (64°N) for the complete period of analysis (Aug 1993 to Oct 2006). We see the effect of some disadvantageous antenna radom models used at most Swedish sites (except Onsala) between 1993 and 1996 [Johansson el al. 2002]. Because of this, the period before mid-1996 has been excluded from further investigation in this analysis. We also see non-linear behavior in the vertical position. This "banana"-shape, (or possibly a change of vertical rate by 2003 or 2004) is visible in most of our high latitude sites (possibly above 55°N) and seems to be more pronounced towards north. We also stress that long uninterrupted time series are needed to see this phenomenon. The cause of the bent vertical time series is not yet understood but we can think of a number of candidate causes.

One candidate may be the modeling of tides. Watson et al. (2006) show that aliasing effects may cause velocity differences depending on the choice of tide model for the GPS analysis. Data from a set of global IGS sites for the 5 year period 2000.0 to 2005.0 was analyzed using GAMIT/ GLOBK applying the IERS 2003 and IERS 1996 (denoted IERS 1992 in the paper) tide models respectively. The results showed latitude dependent differences in vertical velocity of ~-0.35 mm/yr at high latitudes increasing to ~+0.2 mm/yr at equatorial latitudes (symmetric about the equator).

In our regional analysis of the BIFROST network, we have consistently used the IERS 1996 tide model. The global sub-network from SOPAC have also been analyzed using the IERS 1996 tide model up to beginning of 2006, when SOPAC changed to IERS 2003 in their processing. Possible limitations in the old IERS 1996 tide model may therefore contribute to the bent vertical time series. Therefore, the choice has been to perform our own analysis of a network with global coverage (Figure 3-1), applying the IERS 2003 tide model. Then we have combined the BIFROST sub-networks with this network in order to give our results a global connection, although this cause some inconsistency because the regional BIFROST analysis have been performed using the old IERS 1996 tide model. See further Lidberg et al. [2007b].

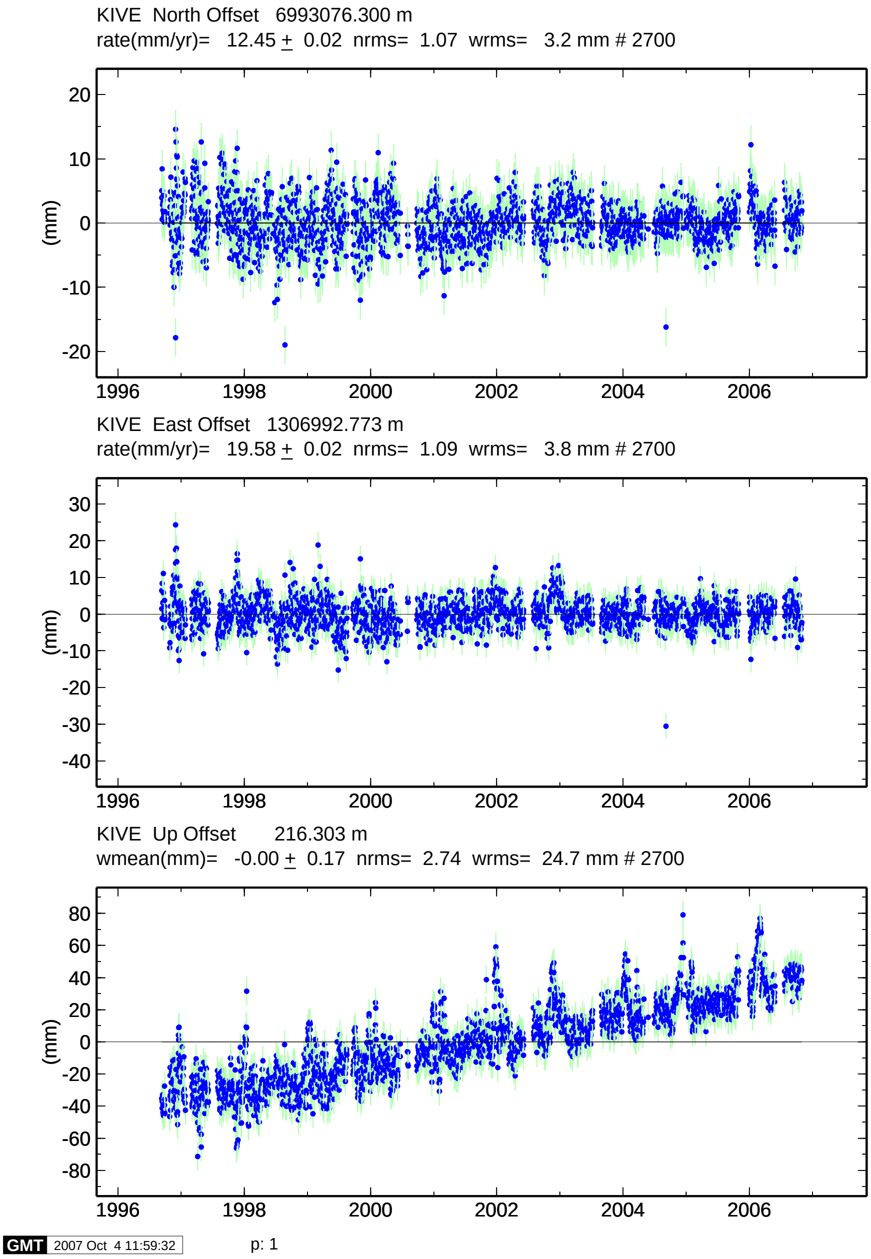


Figure 3-3. Example from KIVE of position time series (n,e,u), before editing. The outliers in the vertical component are considered to be caused by snow accumulation on the GPS antenna. A linear trend has been removed from the north and east time series before plotting.

In Figure 3-3 we show an example from Kivetty (KIVE) of time series plots (n,e,u) of daily position estimates. The vertical "banana-shape" is maybe not eliminated, but at least heavily reduced. We see occasionally large outliers in the vertical component, predominantly in winter time. This phenomenon has been attributed to snow accumulation on the antenna, and the samples should therefore be removed in the velocity estimation. It may be noted that in this combined solution the IERS 2003 tide model was used for the global 35 site network, while the regional BIFROST analysis was performed using the old IERS 1996 model.

3.3 Model for Estimating Station Velocities

Station velocities are estimated from daily estimates of positions using an extended linear regression model. When estimating the constant velocity for each component of each station, we simultaneously model seasonal variations by estimating the amplitude of annual and semi-annual sine and cosine functions. The position shifts discussed above are modeled as a step function. Thus six parameters plus one parameter for each shift are estimated for each component. The mathematical expression for the model may be written (Nikolaidis 2002):

$$\begin{aligned} y(t_i) &= a + bt_i + c\sin(2\pi * t_i) + d\cos(2\pi * t_i) \\ &+ e\sin(4\pi * t_i) + f\cos(4\pi * t_i) + \sum_{j=1}^{n_g} g_j H(t_i - T_{gj}) + v_i \end{aligned} \tag{3-1}$$

where t_i are epoch time in years for the daily solutions, *H* is the Heaviside step function, and v_i denotes noise.

3.4 Outlier Editing

The purpose of outlier editing is the removal of erroneous samples from disturbing the estimated station velocities. An additional purpose is to retrieve a “clean” data set that belong to one stochastic distribution where the residuals from the deterministic model (v_i above) can be used for estimating the accuracy in the derived parameters.

We have used the Tsview software [Herring 2003, MIT 2005 *[online]*] for data editing and estimation of station velocities. Tsview is a part of the GGMatlab tools which allows interactive viewing and manipulation of GPS velocities and time series with a Matlab-based graphical user interface.

For data editing we have used an automatic outlier function in Tsview with a 5 sigma rejection level. For northern sites with obvious snow problems we have narrowed this to a 3 sigma rejection level, occasionally supported by manual editing. Roughly some 30 data points per year have been removed using this method. Rejecting almost 10% of the data on the 3 sigma level may be considered much. However, the “snow” samples do not belong to the same stochastic distribution as the “clean” samples. Thus it could be argued that the percentage of rejected data points is irrelevant.

Reliable accuracy estimates of derived station velocities presuppose that the character of the noise of the position time series is known a priori or can be estimated. A common method is to deter-mine the spectral index and amplitude on the noise using maximum likelihood estimation (MLE) (e.g. Williams 2003, Williams et al. 2004). In this work we have however used the “realistic sigma” function of tsview, where formal uncertainties in derived parameters (assuming white noise) are scaled by a factor derived from the residuals assuming a Gauss-Markov process (Lidberg et al. 2007). The noise scaling factor is usually in the range of 3-5.

4. RESULTS

The results from the process above are two 3D velocity fields constrained to the ITRF2000 and ITRF2005 reference frames respectively. The purpose of this work is however to study crustal deformations within the area influenced by the GIA-process. We have therefore remove the plate tectonic motion to present the velocities relative to “stable part of Eurasia”. It turns out that the internal horizontal velocities for the ITRF200 and the ITRF2005 solutions are very similar. In Figure 4-1 we therefore only show the ITRF2005 solution, together with predictions based on a geophysical GIA model.

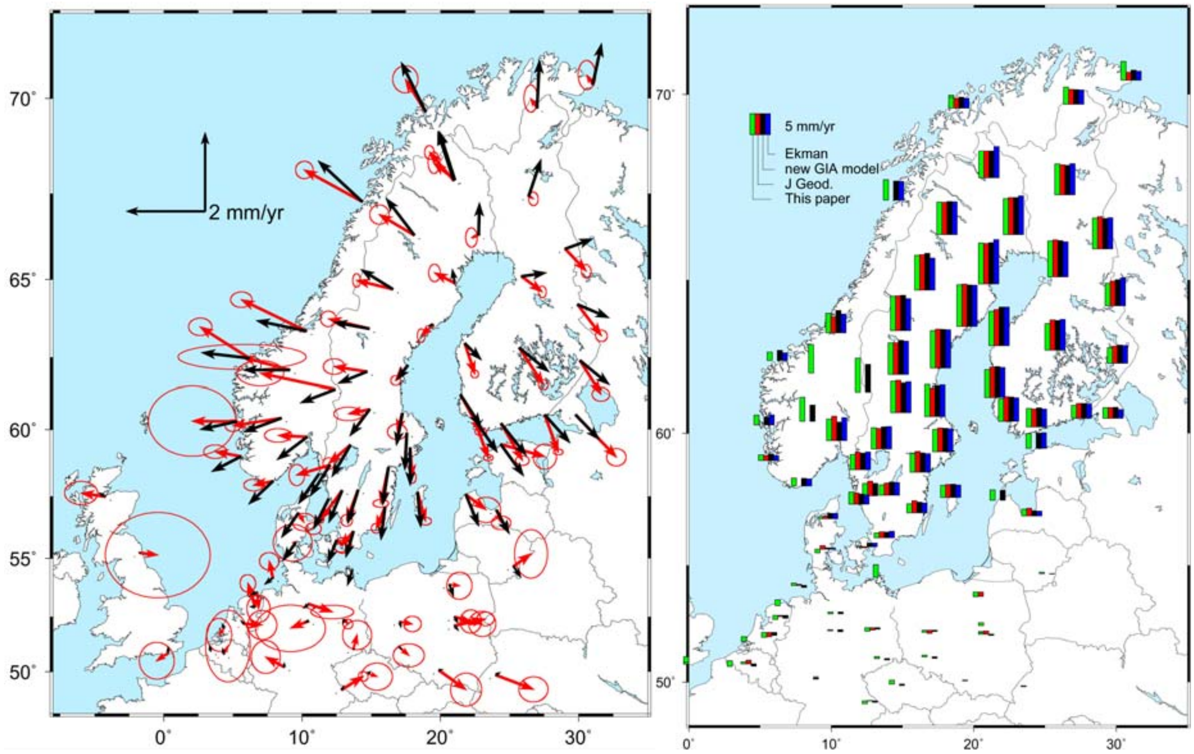


Figure 4-1. Left; horizontal velocities of the new GPS solution (red arrows with error ellipses) and the GIA model predictions (black arrows). Right; vertical velocities from this solution, from Lidberg et al (2007a), the GIA model , and values derived from classic geodesy (tide gauge, repeated leveling, repeated gravity observations (Ekman 1998).

We use an updated version of the BIFROST model presented in Milne et al (2001). The revised model provides an optimum fit to the recent GPS solution in Lidberg et al. (2007).

The model comprises the ice model of Lambeck et al. (1998) and an Earth viscosity model defined by a 120 km thick lithosphere, an upper mantle viscosity of 5 x 10^20 Pas and a lower mantle viscosity of 5 x 10^21 Pas. For comparison, the optimum values obtained for the older GPS solution (Johansson et al. 2002) were, respectively, 120 km, 8 x 10^20 Pas and 10^22 Pas.

5. VELOCITY FIELD FOR USE IN REFERENCE FRAME MANAGEMENT

5.1 The NKG_RF03vel Velocity Model

In order to compare reference frames realised at different epochs in time in an area exposed to significant crustal deformation the different reference frames should be translated to a common epoch of the internal (intraplate) deformation. This means that the coordinates should be transformed in time, and we need a model for these internal deformations. In this study we have used the NKG_RF03vel velocity model, which has been compiled within the NKG Working Group for Positioning and Reference Frames (Nørbech et al. 2006). The intraplate deformation velocities according to this model are shown in Figure 5-1.

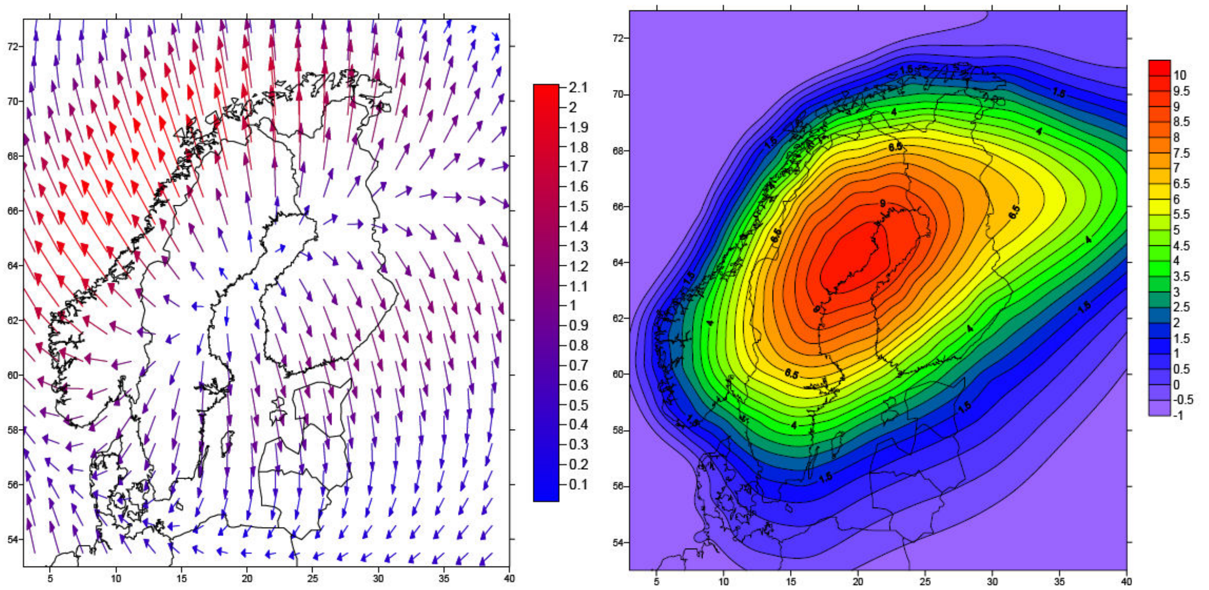


Figure 5-1. The NKG_RF03vel velocity model. See text.

The north and east components originate from the (previous) GIA model developed within the framework of the BIFROST effort and presented in Milne et al. (2001). The velocity field of this model has been transformed (rotated) to the GPS-derived velocity field in Lidberg et al. (2007a).

For the vertical component, the NKG2005LU(ABS) model (absolute land uplift relative to earth centre of mass), developed within the NKG Working Group for Height Determination, has been used. This model origins from the NKG2005LU(APP) model (apparent land uplift relative to sea level) (Ågren et al. 2006 a and c), which is a smoothed version of a combination of the Vestøl model (Vestøl 2006) used in the Fennoscandia area, and the Lambeck model (Lambeck et al. 1998 a and b) used in the Baltic and northern central European area. The apparent land uplift values in NKG2005LU(APP) have been converted from apparent land uplift values to absolute land uplift with the following formula:

$$u_{abs} = (u_{app} + 1.32 \text{ mm/yr})*1.06 \qquad (5\text{-}1)$$

Here uabs is the absolute land uplift relative the earth centre of mass, and uapp is the apparent land uplift from NKG2005LU(APP). The constant 1.32 mm/year reflects the absolute sea level rise (for this area of the globe) and the factor 1.06 reflects the geoid rise.

5.2 Comparing the Official National Realizations of Etrs89 in the Nordic Area

In order to compare the different Nordic ETRS89 realisations, we need a common realisation as a reference. For this the results from the NKG2003 GPS campaign (Jivall et al. 2005) have been used. The campaign covers the Nordic and Baltic area, as well as Iceland, Greenland and Svalbard and includes 133 stations. Most of these sites are permanent operating GPS stations. But campaign style GPS sites are added especially in Denmark, Latvia and Lithuania.

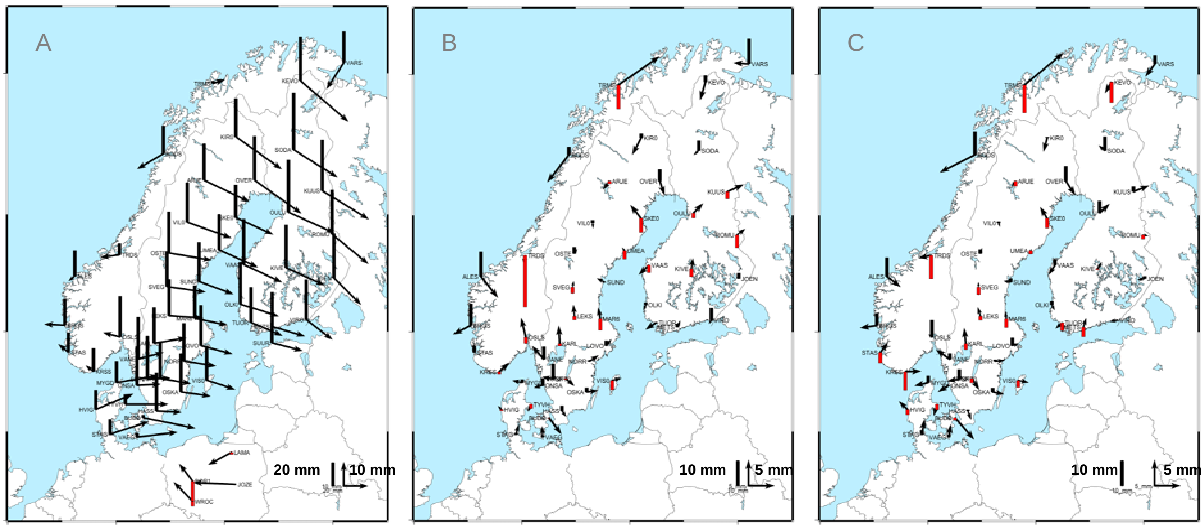
Observations were performed during seven days in GPS week 1238 (week 40, 2003). GPS analysis employed the GIPSY-OASIS-II, the GAMIT/GLOBK and the Bernese software packages. The result was presented in ITRF2000, epoch 2003.75, and was designated NKG_RF03. The complete work was coordinated by the working group for Positioning and Reference Frames within the Nordic Geodetic Commission (NKG).

In the evaluation of the official national ETRS89 realizations, we first computed the coordinate differences to NKG_RF03. In order to arrive at an unbiased result, this comparison requires, however, that NKG_RF03 is translated to the plate tectonic epoch of 1989.0. Therefore, we transformed NKG_RF03 from ITRF2000, epoch 2003.75, to ETRS89 using the official method (Boucher and Altamimi 2001). Additionally we performed a reduction for the intraplate deformations from 2003.75 back to epoch 2000.0. This measure was done to (at least partly) correct for intraplate deformations, and reduces the maximum vertical residuals from the 8 cm level to the 4 cm level at some sites close to land uplift maximum. After converting the displacement velocities given in the model NKG_RF03vel as (north, east, up) to the geocentric (X,Y,Z) frame, the corrections for intraplate deformation are applied using the formula:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{EPOCH}^{ITRF\,2000} = \begin{pmatrix} Y \\ Y \\ Z \end{pmatrix}_{2003.75}^{ITRF\,2000} + (EPOCH - 2003.75)\begin{pmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{pmatrix}_{INTRAMODEL}^{ITRF/ETRS}$$

Here, EPOCH is the target epoch, $(\dot{X},\dot{Y},\dot{Z})_{INTRAMODEL}$ are displacement velocities according to the intraplate deformation model (NKG_RF03vel), and 2003.75 is the epoch for the GPS-campaign.

According to the formula, the deformation corrections are applied in ITRF2000 before transformation to ETRS89. Following the ETRS89 memorandum (Boucher Altamimi 2001), the corrections for intraplate deformations should be applied as a last step after the transformation to ETRS89 (and be reduced back to 1989.0 rather than to 2000.0). We note however that because the orientation differences between ITRF and ETRS89 are small in the view of intraplate deformations, it is not important at which stage the corrections are applied.



Statistics of residuals
(n,e,u) and (mm)
A) Mean: -3.4 9.8 25.6
RMS : 6.6 14.1 29.1

B) RMS Dk: 1.8 1.3 0.9
Fi: 1.6 1.4 3.1
No: 3.4 3.6 9.5
Se: 1.7 1.3 3.1

C) RMS Dk: 2.5 2.0 1.8
Fi: 1.3 1.4 3.7
No: 2.7 3.9 7.5
Se: 1.5 1.3 2.5

Figure 5-2. Residuals between NKG_RF03 in ETRS89 and national realisations of ETRS89; (A) NKG_RF03 reduced to internal epoch 2000.0, (B) NKG_RF03 reduced to internal epoch of each national ETRS89 realisation and national 7-parameter fit, (C) NKG_RF03 reduced to internal epoch 2000.0 and a national 7-parameter fit. The NKG_RF03vel velocity model.

Figure 5-2(A) shows the residuals (first minus second) between NKG_RF03 in ETRS89 and reduced to intraplate deformation epoch 2000.0 and the official national ETRS89 realisations (Table 5-1). Note that the residual pattern is different and smaller in Norway compared to Denmark, Finland and Sweden. This may be because in ITRF92, ITRF96 and ITRF97 the NUVELL-1a NNR rotation pole was used for Eurasia, while the rotation pole was estimated from the observations in ITRF93 and ITRF2000.

Figure 5-2(B) shows in one plot the residuals of 7-parameter Helmert transformations for each country, when NKG_RF03 are transformed to the national ETRS89 realizations, where

NKG_RF03 in ITRF2000, epoch 2003.75, are first reduced for internal deformations to the epoch of the national ETRS89 realizations.

Figure 5-2(C) shows in one plot the residuals for each country when NKG_RF03 is transformed to the ETRS89 with internal deformation epoch 2000.0, and then a 7-parameter fit to each national ETRS89 realization.

The root-mean-square (RMS) values presented in Figure 5-2 are computed from the plotted residuals (without removing any bias term). In Figure 5-2(A), the mean value of the residuals are presented, while the mean of residuals in Figure 5-2(B) and 5-2(C) are close to zero due to the applied transformations.

In terms of accuracy, the methods in 5-2(B), and in 5-2(C) are equal, although there are slightly different residual patterns. It can therefore be argued that it is not necessary to treat the national ETRS89 realisations as different intraplate deformation epochs, but that one can use 2000.0 as the common epoch. The explanation may be that the Helmert transformation absorbs sufficiently well the residual deformation in Norway and Finland that has not been corrected for in 5-2(C), while the difference in epoch for Sweden (1999.5 and 2000.0 or 0.5 cm level) is of minor importance.

Table 5-1. National ETRS89 realisations in the Nordic countries. (e.g. Mäkinen et al. 2003)

Country	Denmark	Finland	Norway	Sweden
System/ campaign	EUREF-DK94	EUREF-FIN	EUREF-NOR94 EUREF-NOR95 EUREF-NOR96	SWEREF 99
Internal epoch	1994-09-15	1997.0	Appr. 1995	1999.5
Based on ITRF	ITRF92	ITRF96	ITRF93	ITRF97
Published in	Frankhauser and Gurtner [1995]	Ollikainen et al. [2000]	Kristiansen and Harson [1999]	Jivall and Lidberg [2000]

We note the good agreement of the internal geometry between the results of the different GPS campaigns (2 mm level horizontal and <5 mm level vertically – slightly worse in Norway), and 1 cm level and a few cm level for the horizontal and vertical components respectively when comparing the ETRS89 realisations. Also very good and more than sufficient for most (all?) practical applications, we conclude that the challenge is not in how to create a coordinate set with good internal geometry, but how to create a coordinate set based on a well defined reference frame and how to translate this to (for the European case) the ETRS89.

6. SUMMARY

We have shown agreement between GPS-derived station velocities and predictions from an updated GIA model at the 0.5 mm/yr level in horizontal and vertical components. The crustal motions we observe in northern Europe can, on average, thus be explained to this level of accuracy! Some individual sites, usually with short observation span, may have larger discrepancies.

A model for intraplate deformations, NKG_RF03vel developed within the NKG cooperation, has been used for accounting the Fennoscandia GIA process. It is able to represent about 90% of the observed deformations. This model should be considered as a first attempt to account for European intraplate deformations and should be exposed to continuous improvements.

We have used a common nordic reference frame, NKG_RF03, to confirm the good agreement between the national realizations of the ETRS89 within the Nordic countries. We have also used the NKG_RF03vel model to correct for intraplate deformations due to the Fennoscandia land uplift phenomenon, and we get eccelent agreement between the internal geometry of the NKG_RF03 and the national realisations of ETRS89.

ACKNOWLEDGEMENT

The work to compute GPS station velocities has been performed as a part of the BIFROST effort, and especially the Geo-group of the Onsala Space Observatory. The work with the GIA model has to large extent been done by Glenn Milne, Durham University. The implementation of the results for the purpose of reference frame management has been done within the cooperation of the Nordic Geodetic Commission, NKG.

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BIOGRAPHICAL NOTES

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