New velocity solutions from 13 years of BIFROST activities

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Abstract

We present an updated 3D velocity field of the Fennoscandian Glacial Isostatic Adjustment (GIA) process derived from more than 4800 days (13 years) of data at more than 80 permanent GPS sites. We use the GAMIT/GLOBK and the GIPSY/OASIS II software packages for GPS analysis. We compare the results obtained from GAMIT/GLOBK; GIPSY in PPP mode (Precise Point Positioning); and GIPSY with ambiguity fixing. The solution has an internal accuracy at the level of 0.2 mm/yr (1 sigma) for horizontal velocities at the best sites. We present our results both in the ITRF2000 and in the new ITRF2005 reference frames, and discuss the differences. Our vertical velocities agree with results derived from classic geodetic methods (tide-gauge, repeated levelling, and repeated gravity observations) at the 0.5 mm/yr level (1 sigma). We also compare the observations to an updated GIA prediction model tuned the new data and get agreements on the sub-millimeter level.

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 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).
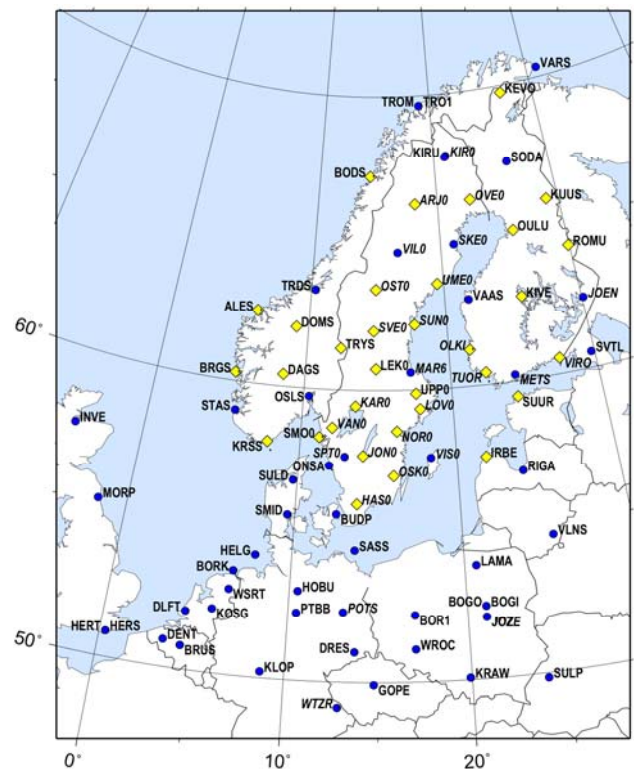

Figure 1. The extended BIFROST network. Filled dots mark sites available in the public domain through EPN or IGS. Diamonds mark sites in national densifications.

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).

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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 apply-ing the double differencing approach. The results are computed loosely constrained Cartesian coord-inates 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 analy-sis 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 cor-rections 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). Using GLOBK it is also possible to combine several days (and years) of GAMIT results and estimate initial site positions and velocities, and apply constraints for reference frame realization in one step. We have however not used this facility in this study.

The measure to solve for a scale factor in the GLOBK step may be put in question. Our principal argument for doing so is that we do not trust the long term stability in the scale achieved from GPS analysis, given the applied processing strategy. See further the discussion in Lidberg et al (2007).

3.2.   Reference frame realization

The purpose of our study is to derive a 3D velocity field of the deformation of the crust in Fennoscan-dia dominated by the ongoing GIA process. In or-der to resolve the slow and small-scale deforma-tion of the region, a terrestrial reference frame (TRF) consistent over the period of analysis is needed. We also would like to avoid pertirbations 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 new ITRF2005 (Altamimi et al. 2007) reference frames.

Our a priori choice has been to follow the strategy applied in Lidberg et al. (2007), where the regional BIFROST analysis was combined with global networks analyzed by SOPAC, comprising major part of the IGS sites. The sites used for refe-rence frame realization of this combined regional and global analysis are shown in Figure 2. For the ITRF2000 realization we needed to use sites which are well determined in ITRF2000 and whose posi-tion time series are stable (low noise, no non-linear behaviour etc) for the analyzed time span (see fur-ther discussion in Lidberg et al 2007). The ITRF 2005 is computed from time series of position estimates. Therefore shifts have been introduced in the stations position and velocity estimates of the ITRF2005 solution, when considered appropriate. Thus it has been possible to find 78 candidates for reference frame realization that fulfils the stability criterion, compared to 43 for ITRF2000.
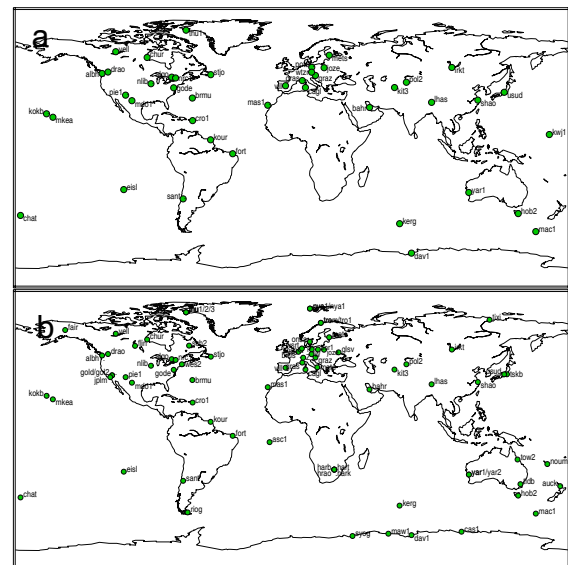

Fig 2. Sites used to as candidates for constraining the combined BIROST + SOPAC global analysis to ITRF. A: the 43 sites used for ITRF2000. B: the 78 sites used for ITRF2005. See text.

3.3.   Evaluation of TRF realization

Figure 3 shows the number of sites actually used and post fit residuals in the realization of the ITRF2000 and ITRF2005 reference frames for the combined regional BIFROST and global SOPAC analysis.
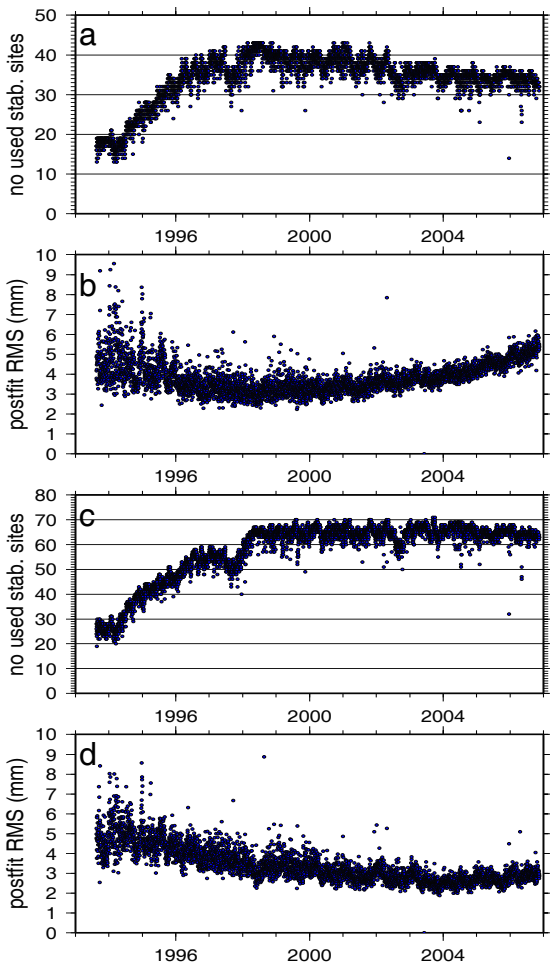
Fig 3. Number of used sites and Postfit RMS (mm) in daily stabilization. A, B: ITRF2000, C, D: ITRF2005. See text.

For the ITRF2000 stabilization in Figure 3a and b we see an improvement in the results up to about 1998. But then we also see a slight decrease in the results after about 2000 (the RMS decrease first, then increase after 2000 – opposite for used sites). For the ITRF2005 stabilization in Figure 3c and d we see also here an improvement up to about 1998, but then the results are stable at a high accuracy level from 1999. Our interpretation of this is that the new ITRF2005 have a better internal accuracy compared to the older ITRF2000.

Figure 4 shows de-trended time series plot of daily position estimates in ITRF2005 from Vilhel-mina (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 possi-bly a change of vertical rate by mid 2003 or early 2004) is visible in most of our high latitude sites (possibly above 55°N) and seems to be more pro-nounced 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 (see discussion in section 7).
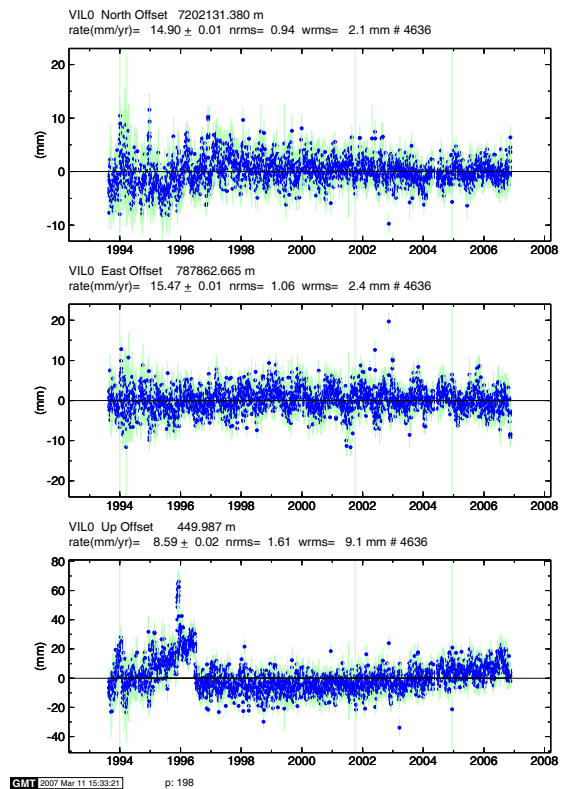

Fig 4. Detrended time series plots of daily position estimates (n,e,u) from Vilhelmina (VIL0) (64°N) for the complete period of analysis (Aug 1993 to Oct 2006).

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).
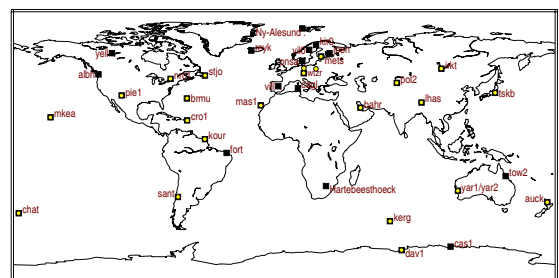

Fig 5. Network of 35 sites (black squares) and the 23 sites (light circles) used for reference frame realization.

In our regional analysis of the BIFROST net-work we have consistently used the IERS 1996 tide model. The global sub-network from SOPAC have also been analyze

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.

Based on the discussion above we have perform-ed our own analysis of a small global network with global coverage including 35 selected sites, apply-ing 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, without using the products from SOPAC. The global network is supposed to:

- cover the globe sufficiently well
- connect the regional and the global sub-networks (8 common sites – cp. Fig. 1 and 5)
- include a sufficient number of "good" sites for reference frame realization (23 sites).

Our 35 sites global network is shown in Figure 5 (black squares) together with the 23 sites used as candidates for reference frame realization (light circles).

In Figure 6 we show an example from Vilhelmi-na of a de-trended time series plot of daily vertical position estimates. The vertical "banana-shape" is maybe not eliminated, but at least heavily reduced. 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.
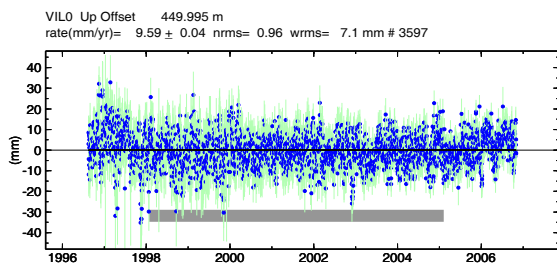

VIL0 Up Offset   449.995 m
rate(mm/yr)=   9.59 ± 0.04 nrms= 0.96 wrms= 7.1 mm # 3597

Fig 6. De-trended time series plot of daily vertical posit-ion estimates for Vilhelmina. The regional analyses have been combined with the global network in Figure 5.

3.4. Two step reference frame approach

In our analysis we have "stable" sites with +10 year observations, and "new" sites with <5 year. If the vertical time series in our network still show a bending shape, then a new site with data from e.g. 2002 will get a biased high vertical rate compared to sites with 10 years data. We also would like to take advantage of the old stable site we have in our BIFROST network to improve velocity estimates at the more recent sites.

Therefore we have applied a two step approach for reference frame realization for our final results:

1. First we determine position and velocity for 27 "good" sites (no breaks in time series etc during the complete period 1996 to 2006), based on the 7 year period 1998.0 to 2005.0 (grey marker in Figure 6).

These regional reference frame sites (italic site id in Fig. 1) are mainly from Sweden, some Finnish sites, and some IGS sites from continental Europe.

2. In the second step we apply a 6-parameter transformation (no scale) of all daily solutions to the regional frame defined in 1.

The procedure above has been carried out booth using the ITRF2000 and the ITRF2005 reference frame. For outlier editing in stage 1, and for the se-lection of "good" sites, we have used the "tsview" tool (Herring 2003). While computing the station position and velocity, we have simultaneously estimated parameters for annual and semi-annual seasonal variations.

3.5. Time series analysis and data editing

The outcome of the procedure described above is daily station positions in a well defined reference frame for all the sites in the BIFROST network. The procedure also has the effect of reducing the noise in the time series, where the common mode noise, evident in global GPS networks, has a con-siderable contribution. An example of time series from Kivetty (Finland) is given in Figure 7.
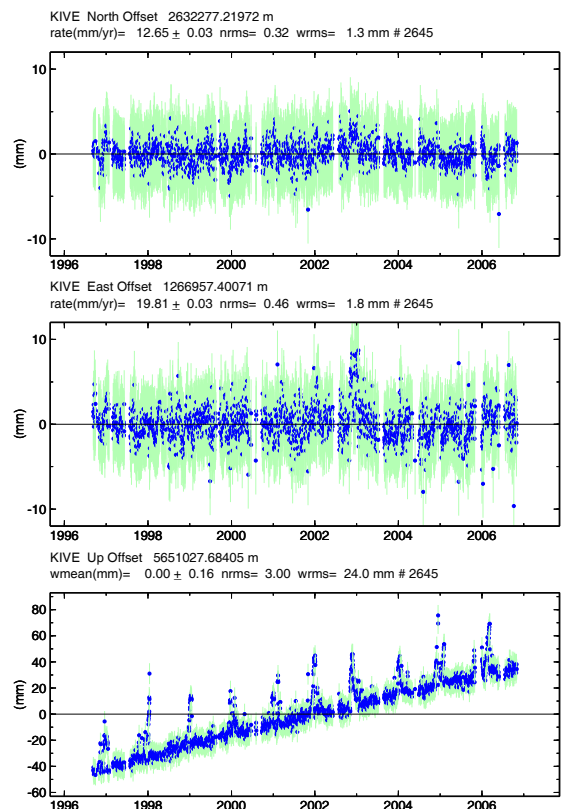

KIVE North Offset 2632277.21972 m
rate(mm/yr)= 12.65 ± 0.03 nrms= 0.32 wrms= 1.3 mm # 2645

KIVE East Offset 1266957.40071 m
rate(mm/yr)= 19.81 ± 0.03 nrms= 0.46 wrms= 1.8 mm # 2645

KIVE Up Offset 5651027.68405 m
wmean(mm)=   0.00 ± 0.16 nrms= 3.00 wrms= 24.0 mm # 2645

Fig 7. Time series plots (neu) of daily position estimates for Kivetty (KIVE) after applying the 2 step reference frame approach. The north and east components has been de-trended.

Note the outliers in the vertical component, and occasionally also in horizontal components. This phenomenon has been attributed to snow accumu-lation on the GPS antenna and is most pronounced at northern

inland station (cf. Johansson et al. 2002, and discussion in Lidberg et al. 2007).

The purpose of outlier editing is to remove erro-neous samples from disturbing the velocity estima-tes, and to retrieve a "clean" data set that belong to one stochastic distribution, where the residuals can be used for estimating the precision of the derived parameters. In this study we have (again) used the *tsview* tool to retrieve station velocities in north, east and up components, estimating seasonal para-meters, outlier editing, and introducing shifts in the time series when appropriate.

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" funct-ion of *tsview*, where formal uncertainties in derive-ed 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 pur-pose of this work is however to study crustal def-ormations within the area influenced by the GIA-process. We therefore would like to present our results in relation to the stable part of the Eurasian tectonic plate. To do so we have removed the plate tectonic motion from our ITRF2000 based solution using the ITRF2000 No-Net Rotation (NNR) Absolute Rotation Pole for Eurasia. The velocity field constrained to ITRF2005 is then rotated to best fit the rotated ITRF2000 field. RMS of residuals in this fit is at the 0.1 mm/yr level. The results are shown in Figure 8 and Figure 9.

5. New GIA model

In this section we compare our GPS derived station velocities with predictions based on a geophysical GIA model. We use an updated version of the BIFROST model presented in Milne et al (2001). The revised model provides an optimum fit to the new 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 5×10^{20} Pas and a lower mantle viscosity of 5×10^{21} Pas. For comparison, the optimum values obtained for the older GPS solution (Johansson et al. 2002) were, respectively, 120 km, 8×10^{20} Pas and 10^{22} Pas.

6. Analysis

In order to check our results we look at the horizontal velocities at sites with the longest site records, located at stable part of Eurasia where we initially would assume the

effect from the GIA process to be small. The RMS value of the north and east velocities for the seven sites BOR1, BRUS, JOZE, LAMA, POTS, RIGA, and WTZR is at the 0.5 mm/yr. This indicates a fairly successful reference frame realization, compared to the formal errors of the ITRF2000 Euler pole for Eurasia (0.02 mas/yr or 0.6 mm/yr).
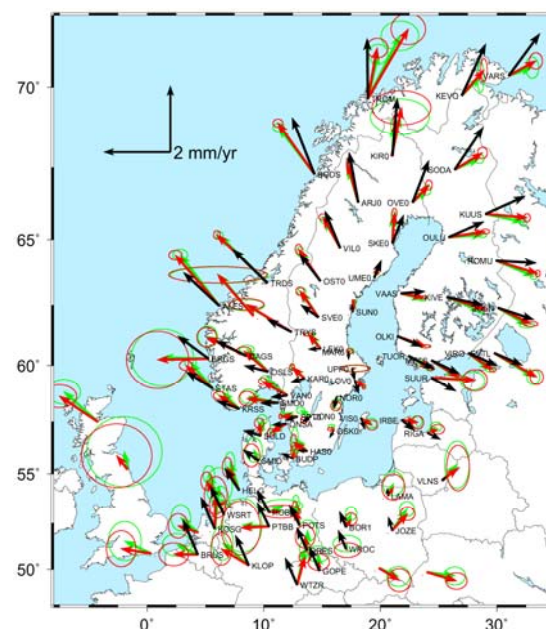

Fig 8. Horizontal station velocities from the ITRF2000 and ITRF2005 solutions (dark grey and light grey arrows with 95% probability ellipses respectively), together with the GIA model (black arrows) rotated to fit the GPS derived velocities.

6.1. Horizontal velocities

Looking at the horizontal velocities in Figure 8, we may notice that these velocities, which should be

relative to "stable Eurasia", may have a bias of several 0.1 mm/yr. The GPS-derived velocities at the best sites in Germany and Poland may not be zero and random, and we would expect zero horizontal velocity close to land uplift maximum, UME0 or SKE0, rather than somewhere between MAR6 and SUN0.

The agreement with the GIA-model is good with RMS of residuals of 0.4 and 0.3 mm/yr for the north and east components for the 71 common points.

6.2. Vertical velocities

In Figure 9 and Table 1 we compare vertical rates from our ITRF2000 and ITRF2005 based solutions to the updated GIA-model and to values presented by Ekman (1998). The latter are based on apparent land uplift of the crust relative to local sea level observed at tide gauges during the 100-year period 1892 to 1991, repeated geodetic leveling in the inland, an eustatic sea level rise of 1.2 mm/yr, and rise of geoid following Ekman and Mäkinen (1996). The standard errors of these rates (here denoted "Ekman") are estimated to between 0.3 and 0.5 mm/yr (larger values for inland stations).
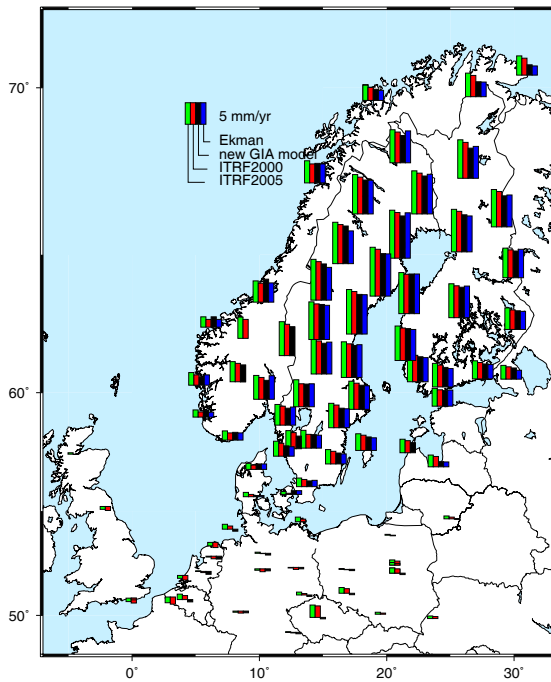
Fig 9. Vertical station velocities from the ITRF2005 and ITRF2000 solutions (two leftmost bars), the updated GIA model (black) and values according to Ekman (rightmost bar when available).

First we note the differences in vertical velocities (mean difference 0.4 mm/yr) between GPS sol-utions constrained to ITRF2000 and ITRF2005. Such a systematic difference has been reported from the work with ITRF2005 (e.g. Altamimi 2006), but our difference is somewhat smaller than expected. We also note that booth our GPS solutions give larger vertical rates compared to booth the new GIA-model and the tide-gauge rates presented by Ekman.

7. Discussion

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.

Table 1. Statistics from comparison of vertical rates from the solutions presented here, the updated GIA-model, and values from Ekman (1998). See text.

Difference from ITRF2000 based solution (mm/yr)	Mean	Standard deviation
ITRF2005 based solution	0.4	0.1
Updated GIA model	-0.4	0.5
Ekman (1998)	-0.5	0.6

The comparison is done by "ITRF2005", "GIA model", etc minus ITRF2000 based solution.

There are also large differences in the northern-most area. We think this is due to remaining effects from the "banana-shaped" vertical time series. We don't understand the causes of this effect yet. However candidates for explanation may be effects from succession of GPS satellite block type (Ge et al. 2005), and contribution from higher order ionospheric terms (Kedar et al. 2003) which have not been corrected for here. The tide models may still contribute to the bent time series since the global sub-network (Figure 5) is computed using the IERS 2003 model, but the regional BIFROST sub-networks are still processed using the old IERS 1996 tide model.

In order to achieve a considerable increase in accuracy of station velocity from GNSS analysis, a number of measures should be considered. A consistent use of the best tide model is obvious. Higher order ionospheric effects should be taken into account. Atmospheric loading may be include-ed at the observation level (e.g. Tregoning and van Dam 2005). New mapping functions are now available (e.g. Tesmer et al. 2007). IGS has now changed from relative to absolute calibrated ant-enna phase center variations (PCVs) in analysis and products. To take advantage of these improve-ments, re-processing of a considerable amount of the IGS-sites would in principle be needed. Espe-cially if the approach of global connection for refe-rence frame realization described here is applied. These efforts have fortunately started (e.g. Steig-berger et al. 2006). It may also be noted that some of the possible improvements may be difficult to implement in practice to get full advantage of them. E.g. the PCV determined in absolute antenna calibration may be valid for an isolated antenna, but these properties may change due to electro-magnetic coupling and scattering effects when the antenna is attached to its foundation (Granström 2006).

The stability in the reference frame is of crucial importance in order to determine un-biased abso-lute vertical displacements relative to the earth centre of mass. We note the difference between the latest and former versions of ITRF. Even though ITRF2005 have better internal accuracy (Figure 3), the ITRF2000 derived values are in better agreement with the GIA model and values obtained from classic geodetic methods. An attempt to derive a GIA-model based on the ITRF2005 GPS velocities gave unreasonable results. A closely related point is the availability of stations within the IGS that have not undergone an antenna installation change for >10 years. The number of such stations is limited.

We consider our results to be very good from the perspective of applications like geodetic reference frame management for GIS applications and "geo-referencing". However, for sea level work (using booth GPS and tide gauge observations), aiming at the 0.1 mm/yr level grate care must be taken. In order to reach this goal, it is crucial to continue research into long term stability in GNSS analyses as well as reference frame realization.

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