# On the Use of Crustal Deformation Models in the Management of ETRS89 Realizations in Fennoscandia

**Martin LIDBERG, Jonas ÅGREN, Holger STEFFEN, Sweden**

**Key words**: Reference Frames, Crustal Deformations, GIA, Deformation Models

## SUMMARY

ETRS89 has been introduced as a common reference system for Europe. It is managed by EUREF (the International Association of Geodesy Regional Reference Frame sub-commission for Europe) and is coincident to ITRS (International Terrestrial Reference System) at epoch 1989.0. It is thus co-moving with the Eurasian tectonic plate and is practically drifting away from ITRS with roughly 2.5 cm/yr. ETRS89 is mandatory for data exchange as governed by the INSPIRE (Infrastructure for spatial information in Europe) directive within the European Union. Most countries in Europe, and all Fennoscandian countries, have adopted national realizations of ETRS89 that has been endorsed by EUREF.

In Fennoscandia, the post-glacial land uplift is up to about 1 cm/year in the vertical, but causes also significant crustal deformations in the horizontal components. This need to be considered in the management and use of reference frames.

This presentation will focus on new models of crustal deformation and their use in reference frame management. The new land uplift model NKG2016LU, which has been developed within the NKG (Nordic Geodetic Commission), and new refined models for Glacial Isostatic Adjustment (GIA) have facilitated considerable improvements in both the horizontal and vertical components. The use of land uplift models in appropriate transformation procedures makes it possible to transform between national realizations of ETRS89 and recent ITRFs (International Terrestrial Reference Frames) at the few mm level, which is a necessity for a possible use of a "dynamic reference frame" in parallel to the national realization of ETRS89.

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## 1. INTRODUCTION

Modern society relies on the availability to spatial information in a well defined geodetic reference frame, and satellite positioning in real time. For the Global Navigation Satellite Systems (GNSS), the International Terrestrial Reference System (ITRS) and its realizations through the consecutive improved releases of the International Terrestrial Reference Frame (ITRF) are used (possibly through individual realization for each GNSS were WGS 84 used for GPS is the most well known).

In these global reference frames, coordinates of objects are kinematic due to dynamics of the Earth, *e.g.* plate tectonics. In Europe, the Eurasian tectonic plate has a rigid motion of roughly a couple of cm/yr towards NE in these global reference frames. Traditionally, the label "kinematic" or dynamic" reference frames have been used, but also "secular" reference frames are used.

Kinematic coordinates, however, are not suitable for many practical applications and instead, reference frames with static or minimized variations in coordinates are widely used in georeferencing. In Europe, the IAG Reference Frame Sub-Commission for Europe (EUREF) has defined the European Terrestrial Reference System 89 (ETRS89) to be co-moving with the Eurasian plate in order to avoid time variations of the coordinates due to plate motions.

In the Nordic and Baltic countries the current national reference frames in use are established during the 1990's or early 2000's. These reference frames are modern satellite based reference frames realized in the European Terrestrial Reference System 1989 (ETRS89). They are also "traditional" in the sense that they may be considered as "static" since coordinates are defined as static at a well defined epoch in time.

These "static" reference frames are (at least so far) very convenient for the GIS community, and maybe even more so for the building and construction community where various kind of CAD software are applied for the design and planning of large infrastructure projects. However, for high precision work using space geodetic techniques, the best available reference frame describing the true position of points at the current epoch need to be utilized. Therefore the relation between the national reference frames and the recent ITRF in current epoch needs to be known.

In Fennoscandia, the post-glacial land uplift is up to about 1 cm/year in the vertical, but causes also significant crustal deformations in the horizontal components. Accurate models of these intraplate deformations therefore needs to be developed and applied for the proper management and use of geodetic reference frames in the Fennoscandia area. The current status of the transformations between the national geodetic reference frames and ITRF2008 are presented in Häkli et al (2017). This paper describe recent developments in the models for the intra plate crustal deformations.

## 2. ABOUT THE ETRS89

The foundation for the development of a uniform high accuracy European Reference Frame (ETRS89 and its realisations) was established when IAG formed the new sub-commission EUREF, and CERCO formed the Working Group VIII on geodesy in 1987. The background was the growing need for geoinformation data in a uniform geodetic reference system for many applications, e.g. surveying, navigation, transportation, and logistics. Important actors were e.g. the car industry and EUROCONTROL (the European Organisation for the Safety of Air Navigation). This forced the survey agencies in Europe to establish a uniform reference frame. The result was the development of the European Terrestrial Reference System 89 (ETRS89) (Adam et al. 2000).

ETRS89 has also been recognised at the European authority level e.g. through the "Inspire Architecture and Standards Position Paper" (Inspire 2010), where it is stated that ETRS89 should be used where allowed, with respect to accuracy limits, and together with EVRF2000 for expressing practical (gravity related) heights.

### 2.1 What is ETRS89?

"The IAG Subcommision for the European Reference Frame (EUREF), following its Resolution 1 adopted in Firenze meeting in 1990, recommends that the terrestrial reference system to be adopted by EUREF will be coincident with ITRS at the epoch 1989.0 and fixed to the stable part of the Eurasian Plate. It will be named European Terrestrial Reference System 89 (ETRS89)." (http://etrs89.ensg.ign.fr/ , sited 2017-02-20)

### 2.2 Realization of ETRS89

According to its definition the ETRS89 is coincident with the ITRS (International Terrestrial Reference System) at the Epoch 1989.0 and fixed to the stable part of the Eurasia tectonic plate (e.g. Boucher & Altamimi, 1992).

The principal formula for the transformation is given in eq. (1) below. $X^E$ is position in ETRS89, $X^I_{YY}$ is position in $\mathrm{ITRF}_{\mathrm{YY}}$.

The skew symmetric rotational matrix includes the rotation rates of the Eurasian plate and describes the plate tectonic motion of Eurasia in ITRS. It take care of the plate tectonic motion from 1989 to the epoch of observation $t_c$ (it rotates back from location at epoch of observation $t_c$, to the plate tectonic epoch of 1989). The knowledge of the rotation of the Eurasian plate has been improved during the years, and therefore the values used have also changed.

The translation $T_{YY}$ is a computational effect due to different stations, observations, techniques, models, etc. between the different realizations of ITRS (different $\mathrm{ITRF}_{\mathrm{YY}}$).

$$X^E(t_c) = X_{YY}^I(t_c) + T_{YY} + \begin{pmatrix} 0 & -\dot{R}3_{YY} & \dot{R}2_{YY} \\ \dot{R}3_{YY} & 0 & -\dot{R}1_{YY} \\ -\dot{R}2_{YY} & \dot{R}1_{YY} & 0 \end{pmatrix} \times X_{YY}^I(t_c) \cdot (t_c - 1989.0) \quad (1)$$

The realization of the ETRS89 are denoted European Terrestrial Reference Frame, ETRFs. Detailed description on how to compute values in $\mathrm{ETRF}_{\mathrm{YY}}$ from results in an ITRF are given in the famous "MEMO" (Boucher and Altamimi, 2011).

## 3. THE SPECIFIC SITUATION IN FENNOSCANDIA

The land uplift, postglacial rebound (PGR) or glacial isostatic adjustment (GIA) (now commonly termed the latter) process in Fennoscandia has been a subject of scientific research for more than a century (e.g., Ekman 1991). It is now recognized to be part of the global process of GIA, which originates from the last glacial cycle culminating about 20,000 years ago. When the load from the ice (thickness of about 2–3 km) was removed, the Earth responded as a viscoelastic body, resulting in vertical – as well as horizontal – displacements towards a new equilibrium (e.g., Milne et al. 2001).

The land uplift model NKG2005LU (Ågren and Svensson 2007) are illustrated in Figure 1. Together with the horizontal model, the complete 3D model are denoted NKG_RF03vel (Nørbech et al. 2006).

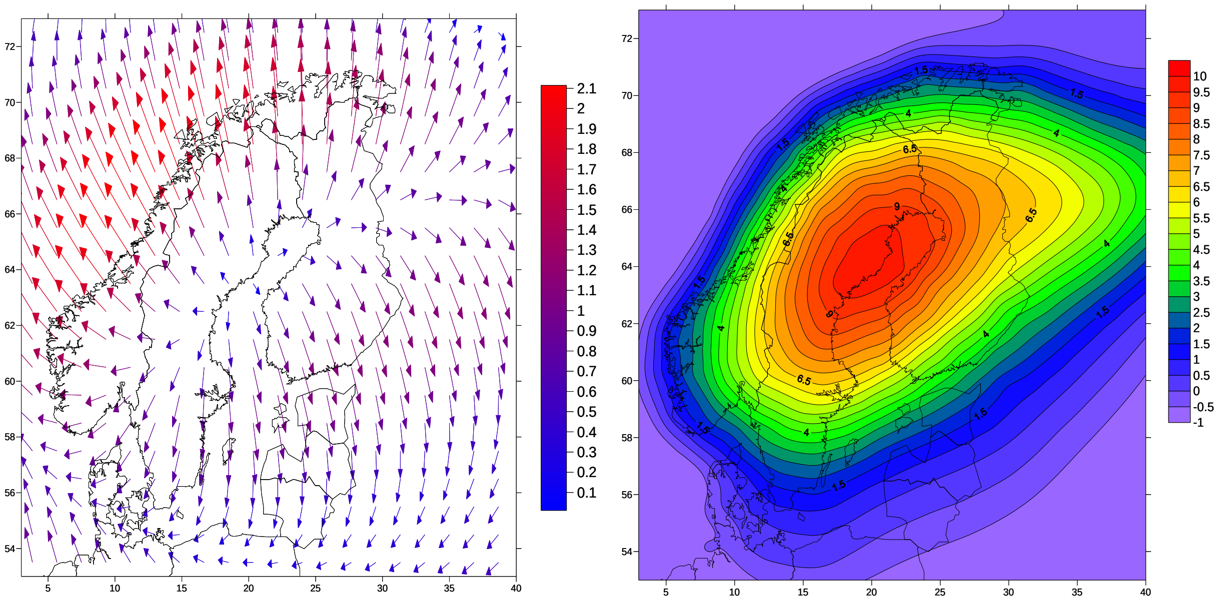


**Figure 1.** The NKG_RF03vel velocity model. Reference for the horizontal velocity field (left) is "stable Eurasia" as defined by the ITRF2000 Euler pole for Eurasia. The vertical uplift rates are "absolute" values relative the earth centre of mass. Units: mm/year.

## 4. REALIZATIONs OF ETRS89 IN FENNOSCANDIA

In the Nordic and Baltic countries national realisations of the ETRS89 have been developed usually during the second part of the 1990s and introduced for national mapping, geo referencing, urban surveying and construction work. Some brief information on ETRS89 realisations in the Nordic countries are given in Table 1.

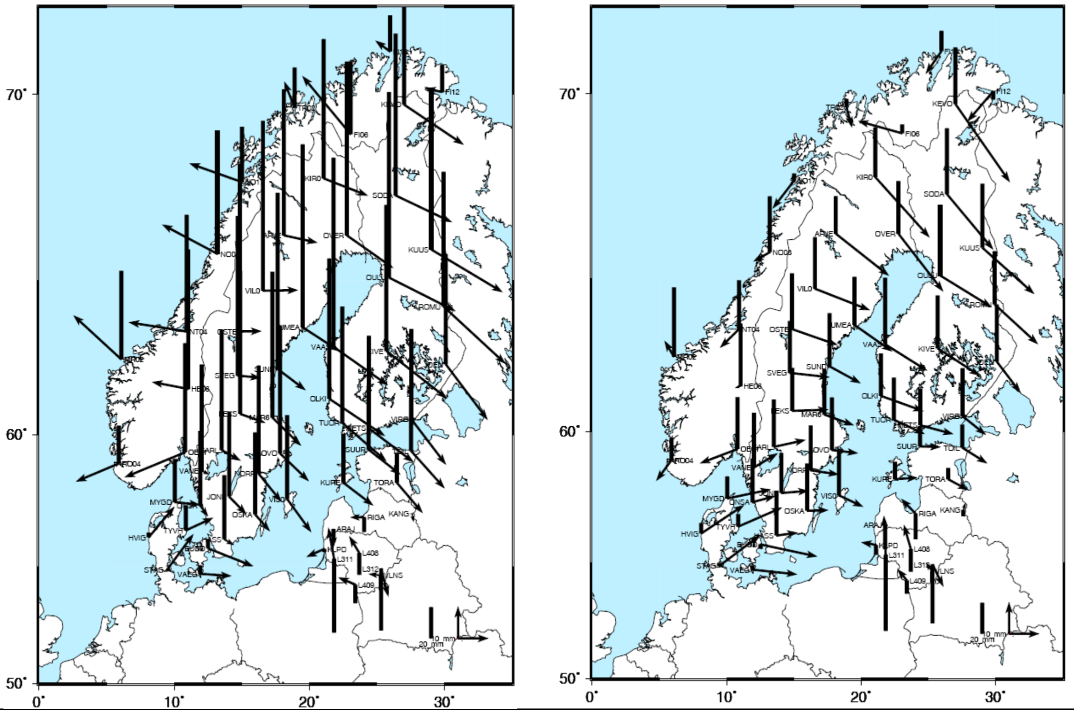
The different ETRS89 realizations agree well in general, but because they were observed at different epochs, they are based on different versions of the ITRF, and they represent different epochs of crustal deformation where the Fennoscandian Glacial Isostatic Adjustment (GIA) process introduce deformation at roughly 1 cm/yr. In total, the differences in realizations are up to a few cm (e.g. Jivall & Lidberg 2000).

**Table 1**. Nordic and Baltic ETRS89 realisations (Häkli et al 2016).

| Country | Name of realization | ETRF version | Realization epoch |
|---|---|---|---|
| Denmark | EUREF-DK94 | ETRF92 | 1994.704 |
| Estonia | EUREF-EST97 | ETRF96 | 1997.56 |
| Faroe Islands | | ETRF2000 | 2008.75 |
| Finland | EUREF-FIN | ETRF96 | 1997.0 |
| Latvia | LKS-92 | ETRF89 | 1992.75 |
| Lithuania | EUREF-NKG-2003 | ETRF2000 | 203.75 |
| Norway | EUREF89 | ETRF93 | 1995.0 |
| Sweden | SWEREF 99 | ETRF98 | 1999.5 |

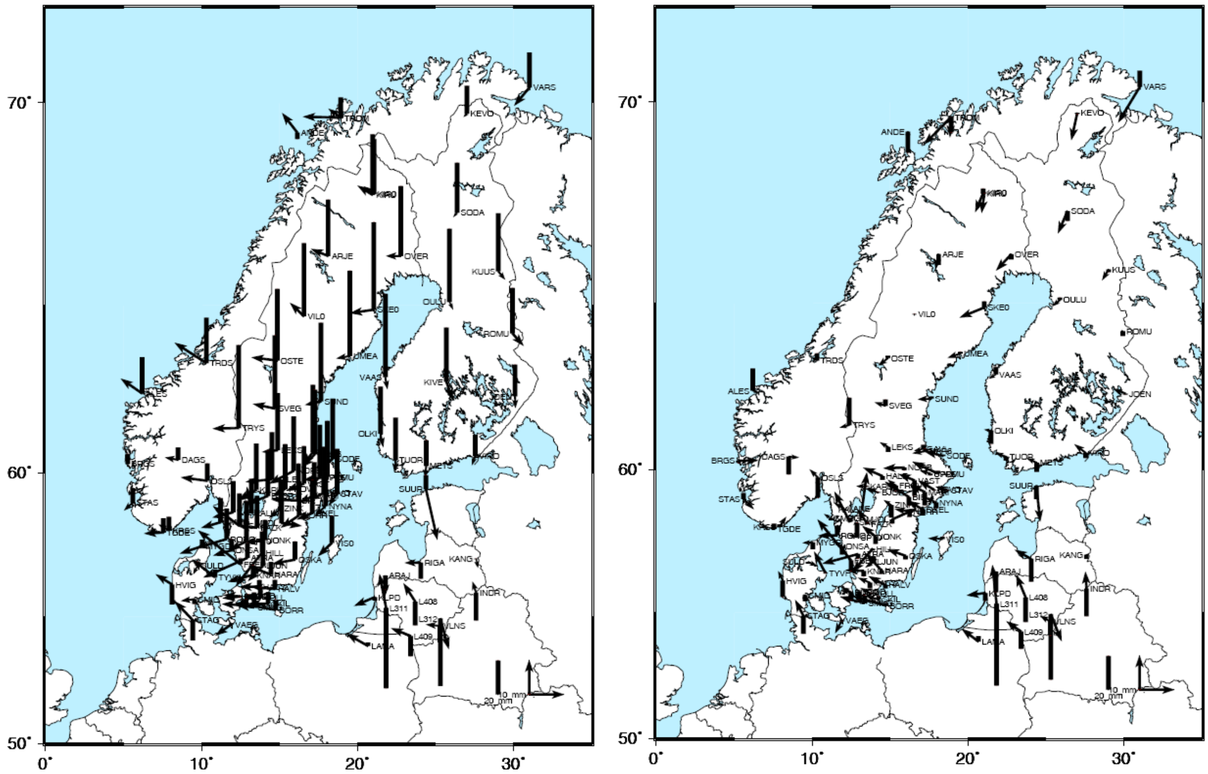
In order to facilitate the development of transformations between the national realizations and recent ITRFs, as well as for evaluation of the agreements between the different national realizations, dedicated NKG GPS campaigns have been performed in 2003 and in 2008 (Jivall et al 2003, and Jivall et al 2008)

The national realizations of ETRS89 in Fennoscandia are compared in Figure 2, where the result from NKG 2008 campaign in ETRF2000 as reference.



| Statistics (mm) | n | e | u | Statistics (mm) | n | e | u |
|---|---|---|---|---|---|---|---|
| RMS | 9 | 12 | 69 | RMS | 8 | 11 | 28 |
| mean | -4 | 5 | 53 | mean | -3 | 7 | 19 |

**Figure 2.** The NKG2008 campaign in ETRF2000 compared to national realzations of ETRS89. **Left**, @ epoch 2008.75. **Right**, @ epoch 2000.0, using a model for intraplate velocities (NKG_RF03vel). Note the importance of using the model.



| Statistics (mm) | n | e | u | Statistics (mm) | n | e | u |
|---|---|---|---|---|---|---|---|
| RMS | 4 | 5 | 24 | RMS | 4 | 4 | 8 |
| mean | -5 | -4 | 16 | mean | 0 | -3 | -3 |

**Figure 3.** Comparing the NKG 2008 and the NKG2003 campaign in ETRF2000. NKG2003 is based on ITRF2000, while NKG2008 is based on ITRF 2005. **Left**, NKG2008 @ epoch 2008.75, NKG2003 @ 2003.75. **Right**, booth @ epoch 2003.75, using NKG_RF03vel model. No fit – just coordinate differences. Note possible accidentally "good luck" in reference frame realization!

## 5. THE NEW LAND UPLIFT MODEL NKG2016LU

An empirical land uplift model is computed directly from the observations using a suitable mathematical method, like for instance least squares collocation. A geophysical GIA (Glacial Isostatic Adjustment) model, on the other hand, is computed in a geophysically meaningful way based on an Earth model, an ice melting history, physical/mechanical laws, etc. A semi-empirical land uplift model is a combination of an empirical model and a geophysical GIA model.

NKG2016LU is a new semi-empirical land uplift model computed in Nordic-Baltic cooperation in the Nordic Geodetic Commission (NKG) Working Group of Geoid and Height Systems. It is computed by combining

1. A new *empirical land uplift model* computed by least squares collocation from GNSS absolute land uplift and spirit levelling from all the Nordic and Baltic countries. The method is very similar to that described in Vestøl (2006), except for that no tide gauges are used for the new model. The GNSS vertical velocities are the results from the BIFROST 2015/2016 calculation in the GAMIT/GLOBK software (March 1, 2016-version, otherwise similar to Kierulf et al. 2014). The GNSS and levelling observations in question are illustrated in Figure 4.

2. A new preliminary *geophysical GIA model* called NKG2016GIA_prel0306 (Steffen et al. 2016). It is based on a spherically symmetric (1D), compressible, Maxwell-viscoelastic earth model applying the viscoelastic normal-mode method. Ice history information is taken from Glaciological Systems Model (GSM) results, a set of 25 different 3D thermo-mechanically coupled glaciological models calibrated against ice margin information, present-day uplift, and relative sea-level records (cf. Tarasov et al. 2012). The best-fitting geophysical Earth model to both the BIFROST uplift and Fennoscandian relative sea-level data simultaneously has a 160 km thick lithosphere, a viscosity of 7 x $10^{20}$ Pa s in the upper mantle, and of 7 x $10^{22}$ Pa s in the lower mantle. The best-fitting GSM ice model is labelled GLAC-71340. The vertical land uplift and geoid change rates are illustrated in Figure 5.

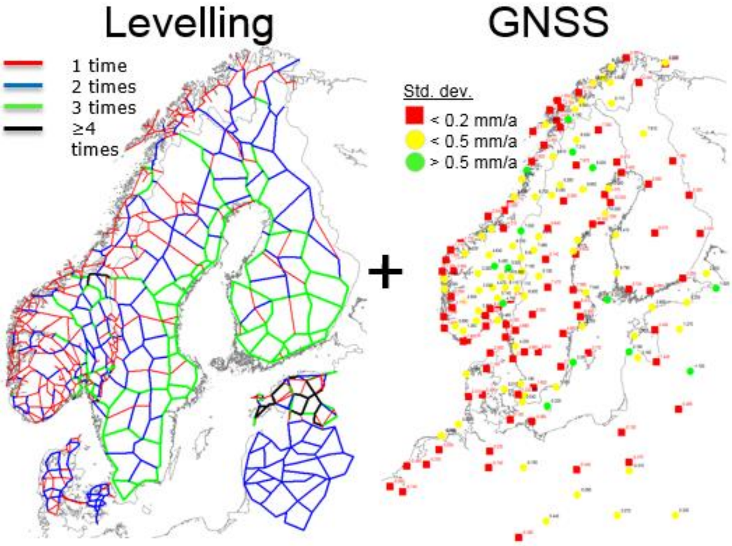
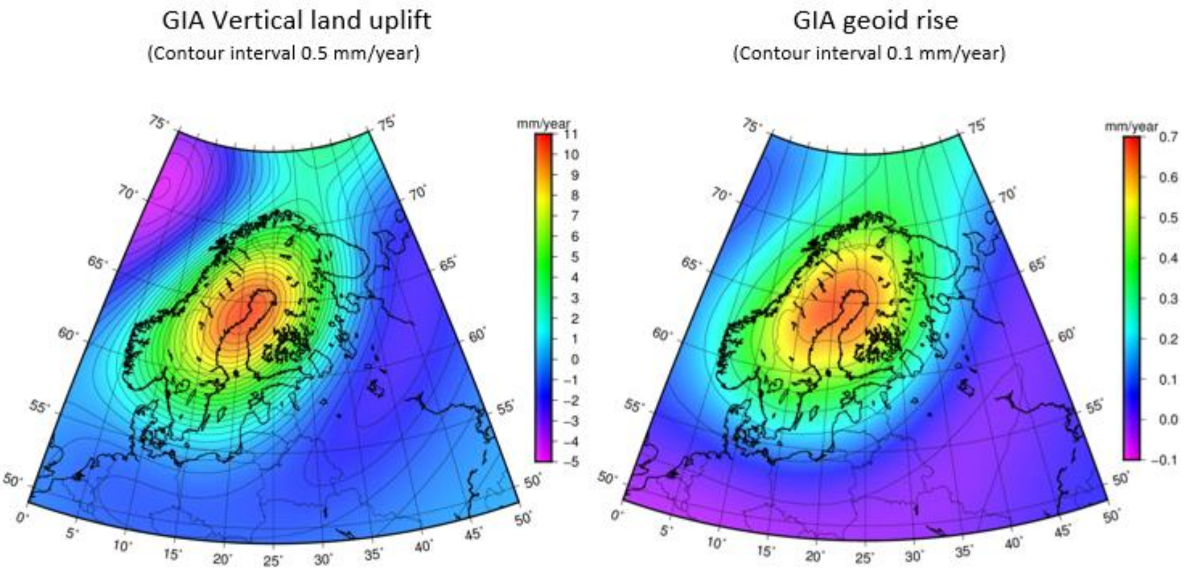


**Figure 4** The geodetic observation used to compute the strictly empirical model utilized for NKG2016LU. The number of levelling lines and estimated standard uncertainties are indicated.


GIA Vertical land uplift
(Contour interval 0.5 mm/year)

GIA geoid rise
(Contour interval 0.1 mm/year)

**Figure 5** The vertical land uplift and geoid rise of the geophysical GIA model **NKG2016GIA_prel0306**.

Now, NKG2016LU gives the vertical land uplift rate in two different ways:

1. NKG2016LU_abs contains the absolute land uplift in ITRF2008 (i.e. relative to the Earth's center of mass), while

2. NKG2016LU_lev provides the levelled land uplift, i.e. uplift relative to the geoid.

Of these, NKG2016LU_abs was first computed from the empirical model and the GIA model using a *remove-interpolate-restore* technique (Vestøl et al. 2016; see also Ågren and Svensson 2007), which can be summarized as follows:

- The GIA model is first *removed* from the empirical model in the observation points.

- The remaining residuals are then gridded by least squares collocation using a 1st order Gauss Markov covariance function with correlation length 150 km (chosen based on covariance analysis) and the given estimated standard uncertainties of the observations.

- The GIA model is finally *restored* to the residual grid to get the NKG2016LU_abs grid.

This implies that the empirical model gets smoothed in the areas with many observations. When moving away from the observations, the NKG2016LU_abs gradually approaches the GIA model. The residuals in the observation points and the residual surface are illustrated in Figure 6.

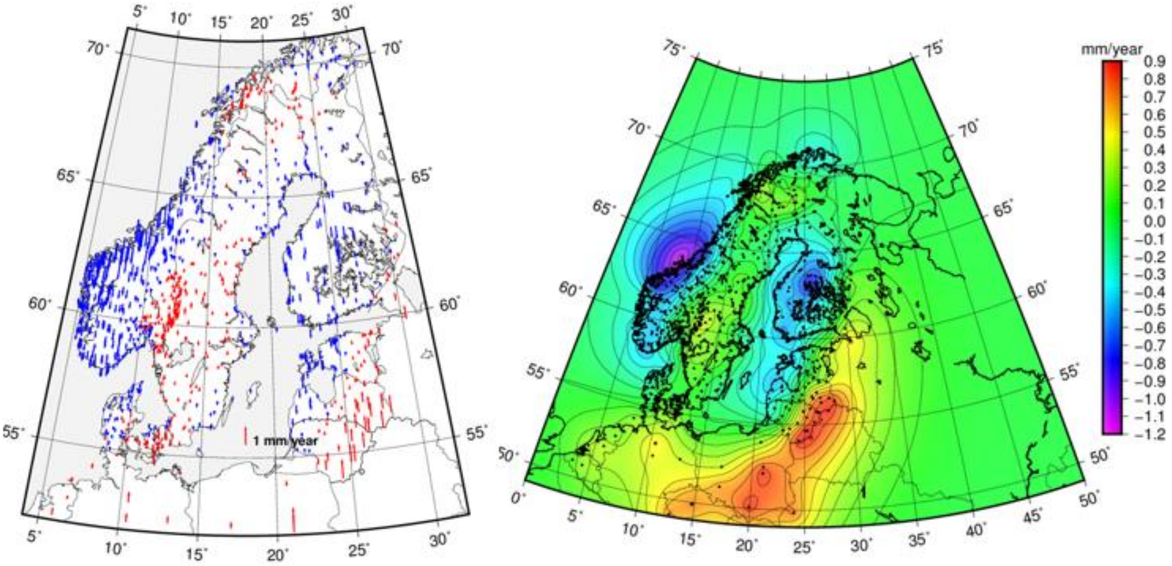


**Figure 6.** *Left:* Illustration of the residuals in the observation points. The scale is given by the 1 mm/year residual in the Southern Baltic Sea. *Right:* The gridded residual surface. Contour interval is 0.1 mm/year.

In the next step, NKG2016LU_lev is derived by removing the geoid rise of the GIA model from NKG2016LU_abs. The geoid should here be interpreted as an equipotential surface that is still rising due to historical ice melting in the past, through Glacial Isostatic Adjustment, but not due to contemporary climate related sea level changes (caused by temperature increase, present day ice melting, etc.) This means that NKG2016LU_lev can be used to correct for the postglacial land uplift that is due to old historic deglaciations in present day sea level studies. The NKG2016LU_abs and NKG2016LU_lev models are illustrated in Figure 7.

Work is presently going on to estimate realistic standard uncertainties for both the NKG2016LU_abs and NKG2016LU_lev models.

It should be mentioned that no apparent uplift model (i.e. uplift relative to Mean Sea Level over a certain time period) is released for the time being. This is mainly motivated by the (accelerating) contemporary climate-related sea level rise, which implies that the apparent land uplift is different from the levelled land uplift and dependent on the chosen time interval. If the apparent uplift is needed, then it is recommended that the user estimates a constant (for a certain time interval and for a certain geographical area) to subtract from NKG2016LU_lev. This is a qualified task that should be made with great care.

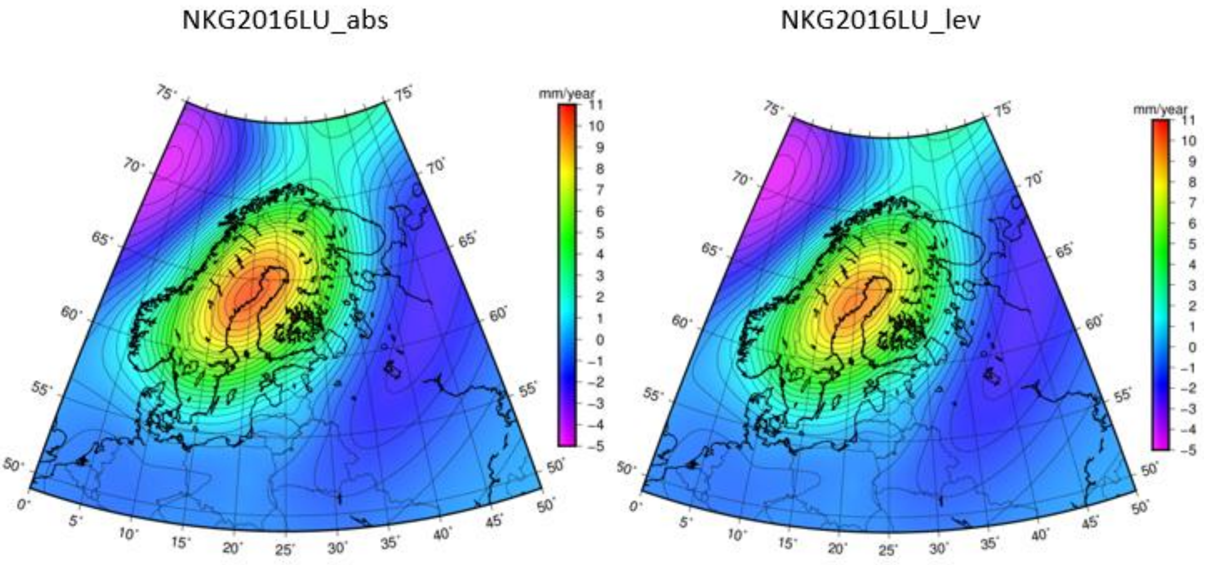


**Figure 7.** Illustration of the NKG2016LU models. Contour interval is 0.5 mm/year. Note the difference to the previous model NKG2005LU (Figure 1), especially in the north east.

### 5.1 A new model for the horizontal component

The GIA model used for the NKG2016LU have been constrained by the GPS-velocity solution basically only in the vertical component. Therefore some additional development have been done to find a best fitting GIA model for the horizontal component. It turns out that the same ice history model as used for NKG2016LU is preferable also for the horizontal component with a slight change of the earth model.

Since the GIA model development is not strictly based on the same reference frame as the GPS velocity solution, it is necessary to apply a velocity transformation from the “GIA reference frame” to the velocities from the GPS analysis. This are usually done using a 3 parameter plate rotation. The residuals between the GIA model and the BIFROST 2015/2016 GNSS velocity solution after such a fit is given in Figure 8.

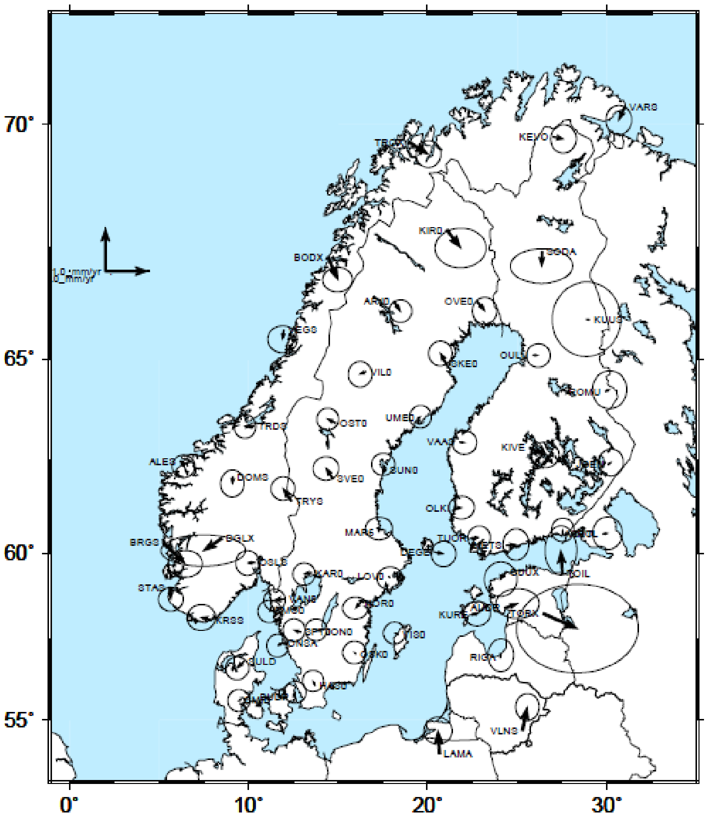


**Figure 8.** Residuals between GNSS velocity solution and GIA model after horizontal fit using 66 vell defined sites. RMS after the fit is 0.22 mm/yr in north and 0.21 mm/yr in the east components.

## 6. SUMMARY

The new models of the GIA process in Fennoscandia do agree well to the observations at the some 0.1 mm/yr level booth in the horizontal component and usually also in the vertical. Although the land uplift reach the 1 cm/yr level, the use of the models of crustal deformations facilitate geodetic precision work at the few mm level also using "static" national reference frame that have established almost two decades ago.

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## BIOGRAPHICAL NOTES

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