A New Transformation Including Deformation Model for the Nordic and Baltic Countries

Pasi HÄKLI, Finland, Martin LIDBERG, Sweden, Lotti JIVALL, Sweden, Torbjørn NØRBECH, Norway, Oddvar TANGEN, Norway, Mette WEBER, Denmark, Priit PIHLAK, Estonia, Ivars LIEPIŅŠ, Latvia and Eimuntas PARŠELIŪNAS, Lithuania

Key words: ETRF2000, ETRS89, Intraplate Deformations, ITRF, Postglacial Rebound, Reference Frame, Semi-dynamic Datum, Transformation

SUMMARY

The ETRS89 is defined to be co-moving with the rigid Eurasian plate to minimize the coordinate variations in time. However, in the Fennoscandian area postglacial rebound causes intraplate deformations up to about 10 mm/yr that needs to be taken into account in maintenance of the national reference frames and in the most accurate georeferencing applications. In this paper we present a new transformation strategy as an implementation of a semi-dynamic datum together with a new common Nordic-Baltic reference frame, designated as the NKG_ETRF00.

The selected transformation follows the recommendations of the EUREF as much as possible. Consequently, the transformation utilizes the de facto transformation formulae and parameters and the conventional frame of the ETRS89, ETRF2000, as recommended by the EUREF. However, additional intraplate corrections and national transformation parameters were applied to serve the requirements of the Nordic/Baltic countries. For correcting the intraplate deformations in the Nordic-Baltic area we have used the existing NKG_RF03vel model. The selected transformation supports any ITRF realizations and observation epochs and can be used to transform coordinates either to national ETRS89 realizations or to the common NKG_ETRF00 reference frame. The NKG_ETRF00 was aligned to ETRF2000 at epoch 2000.0 in order to be close to the national ETRS89 realizations and to coincide with the land uplift epoch of the national height systems.

The results show that the NKG_RF03vel model is working very well as a deformation model; the national transformation residuals (and access to national ETRS89 realizations) are below 5 mm (rms) for most of the Nordic-Baltic countries. However, in this study the model was re-aligned to the ETRF2000 velocities in order to have accurate reference frame realization for the NKG_ETRF00 frame. The accuracy of the velocities is below 0.5mm/yr level (rms) compared to the observed station velocities of the EPN cumulative solution. Also the resultant common frame NKG_ETRF00 is well-aligned to the ETRF2000; a comparison to EPN cumulative solution shows an agreement of about 5 mm (rms).

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1. INTRODUCTION

In Europe, the Eurasian tectonic plate has a rigid motion of roughly a couple of cm/yr towards NE in the global ITRF reference frames. Traditionally, for many practical applications reference frames with static or minimized variations in coordinates are required in georeferencing. 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 [1]. The relation between the ITRF reference frames and ETRS89 realizations is given in the EUREF memo [2] as a 14-parameter transformation. This transformation considers rigid plate motions by using angular velocities of the Eurasian plate allowing minimized station velocities in the ETRS89.

In the Fennoscandian area the postglacial rebound, PGR, (or glacial isostatic adjustment, GIA) phenomenon causes internal deformations to the Eurasian plate that are not taken into account in the de facto EUREF transformation given in [2]. The magnitude of the PGR reaches up to about 1 cm/yr in the vertical, and some millimetres a year in horizontal direction, see e.g. [3]. The Nordic and Baltic ETRS89 realizations were established mostly in the 1990's meaning already 10-20 years of deformations compared to present-day coordinates. The magnitude of the PGR and time span mean that these deformations need to be taken into account in the most georeferencing applications and in maintenance of national reference frames.

As a common challenge, postglacial rebound has been studied during the latest decades with a strong Nordic-Baltic co-operation under the umbrella of the Nordic Geodetic Commission, NKG. The NKG has, for example, published several land uplift models but also common geoid models and transformation methods to maintain national reference frames. In 2003, the NKG carried out a Nordic-Baltic GPS campaign, NKG2003, which resulted in a common reference frame NKG_RF03, deformation model NKG_RF03vel and a transformation procedure from global ITRF2000 to national reference frames that takes into account deformations caused by the PGR [4,5]. In this study the main goals were to establish a new common Nordic-Baltic reference frame and to update the transformations to national ETRS89 realizations from global ITRF reference frames. For this purpose, coordinates from the second Nordic-Baltic-Arctic GPS campaign, NKG2008 [6,7], was used in the transformations.

One example for the need of a common reference frame is an NKG project on the Nordic-Baltic geoid model [8] where a consistent reference frame for heights above the ellipsoid for the GPS-levelling points is needed. For this or any physical height related project, the common frame should be in the same land uplift epoch as the national height systems. In the most Nordic/Baltic countries the national height system is a realization of the EVRS (European Vertical Reference System) [9] and the epoch 2000.0 has been chosen as the conventional epoch. Therefore obvious choice for the epoch of the common frame is 2000.0. It is also advantageous if this frame agree well with the ETRF2000, the conventional frame for the ETRS89 recommended by the EUREF technical working group (EUREF TWG) [2]. With this choice, the common frame would also have small differences to Nordic and Baltic ETRS89 realizations. With these considerations the ETRF2000 at the epoch 2000.0 was chosen as the new NKG common reference, designated as the NKG_ETRF00.

2. METHODOLOGY

2.1 Transformation approach

The developed transformation shall have several qualities: it should include at least a path between the NKG2008 coordinates aligned to the ITRF2008 at the epoch 2008.75 and the Nordic/Baltic ETRS89 realizations but preferably also the common NKG reference frame and any ITRFxx realization at arbitrary epochs in the same transformation procedure.

Primary option in Europe would be to use the recommended de facto transformation by the EUREF [2] but it does not include correction for postglacial rebound and thus, is not applicable as such in the Nordic/Baltic countries. Another alternative would be to use existing NKG2003 transformation approach [5] but it does not support deriving the common frame aligned to the ETRF2000 at the common epoch 2000.0. Besides, the NKG2003 transformation parameters were estimated only for Denmark, Finland, Norway and Sweden. Therefore national transformation parameters should be defined at least for the Baltic countries but probably the NKG2003 parameters might need updating as well. In [10], we discussed about other possibilities to perform the transformation. We concluded to use a method that is as standardized as possible, leading to the EUREF transformation with some amendments to fulfil the Nordic-Baltic demands.

The selected transformation qualifies all preset requirements: it can be used to transform between any ITRF solution at arbitrary epoch, Nordic/Baltic ETRS89 coordinates and the common NKG reference frame, see Fig. 1. The EUREF transformation is used to transform coordinates from ITRFxx at the epoch of observations (tc) to the conventional frame of the ETRS89, i.e. ETRF2000, keeping the epoch intact (shown inside a grey-shaded box grey in the figure). We added subsequent intraplate corrections between the epochs tc and 2000.0 to obtain coordinates in the common NKG_ETRF00 reference frame aligned to the ETRF2000 at the epoch 2000.0. The national transformation parameters $P_{NKG,CC}$ were defined between the NKG_ETRF00 and intraplate corrected national ETRS89 coordinates. The national coordinates must be corrected to the epoch 2000.0 to minimize the deformations between the coordinates and thus, to enable accurate parameters for the similarity transformation. In addition to different versions of the ETRF (yy), the national parameters take into account any possible systematic differences between national densification and the original ETRFyy solution, thus optimizing the accuracy of the transformation.

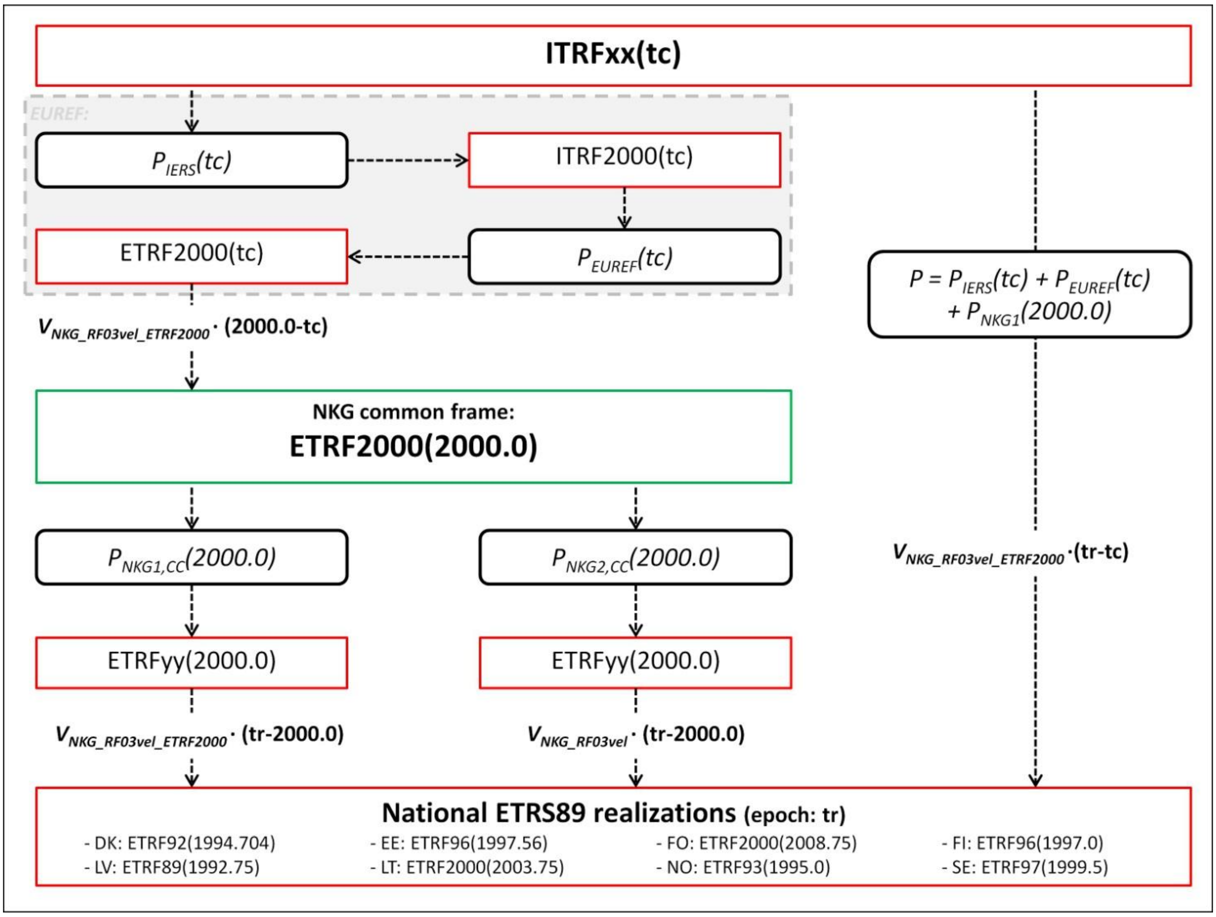


Figure 1. NKG2008 transformation from ITRFxx coordinates at an arbitrary epoch to the national ETRS89 realizations. Left-hand side path shows the step-by-step transformation and right-hand side the direct transformation with merged parameters and intraplate corrections. $V_{NKG\_RF03vel\_ETRF2000}$ is a correction for intraplate deformations from the re-aligned NKG_RF03vel model and $V_{NKG\_RF03vel}$ from the original NKG_RF03vel model. The parameters P_{NKG1} and P_{NKG2} are seven parameters for the similarity (Helmert) transformation at the epoch 2000.0.

Depending on source and target coordinates, the transformation can include only part of the chain or full path. The full step-by-step transformation from ITRFxx coordinates at an arbitrary epoch to the national ETRS89 coordinates (left-hand side path in the Fig. 1) can be simplified by combining (summing) transformation parameters and intraplate corrections (right-hand side path). In the figure the transformation is targeting coordinates in the national ETRS89 realizations but any step can be reversed to produce desired target coordinates. More detailed explanation on different transformation steps along with the formulae are given in [10].

2.2 Re-alignment of the NKG_RF03vel model

The purpose of the original NKG_RF03vel model is to estimate crustal deformations caused by the postglacial rebound. The model has been considered to correct for the deformations in the Nordic area without a need for a rigorous alignment to any reference frame. Any possible systematic differences have been described in a subsequent Helmert transformation. However, when such a model is used to define final coordinates without further transformations, it is crucial that the model is well-aligned to the corresponding reference frame. In such case any biases would propagate into the resulting coordinates.

In the selected transformation one important purpose of the NKG_RF03vel model is to represent ETRF2000 velocities in order to produce accurate NKG_ETRF00 coordinates in the ETRF2000. Therefore the modelled velocities should be well-aligned to the ETRF2000. On the other hand, intraplate corrections are also applied to national ETRFyy coordinates but in this case possible biases between ETRFyy and NKG_RF03vel velocities are absorbed in the defined Helmert parameters and thus biases do not propagate to the coordinates.

In order to estimate the quality of the NKG_RF03vel model in the ETRF2000, we evaluated it with observed GNSS station velocities by using most recent cumulative solution from the EUREF Permanent Network (EPN). The EPN cumulative solutions are updated every 15 weeks and are available both in the latest ITRF (or corresponding IGS) realization and ETRF2000. We have used only stations that are categorized as class A stations meaning that they have high-quality coordinates and velocities [11,12]. At the time of the study the most recent solution covered data up to GPS week 1785 [13], denoted hereafter as the EPNC1785.

In this study it was found out that the NKG_RF03vel model is not optimally aligned to the ETRF2000 velocities of the EPNC1785, see results in section 3.1. In the context of a common reference frame realization any biases are not acceptable and therefore the velocities of the NKG_RF03vel model were re-aligned with a Helmert transformation using seven rate parameters. These re-aligned velocities are designated as $V_{NKG\_RF03vel\_ETRF2000}$ in the Fig. 1. In the figure 1 one may observe that use of the original NKG_RF03vel model ($V_{NKG\_RF03vel}$) in transformations between the NKG_ETRF00 and national coordinates is permitted too. This was considered useful in some cases and therefore associated transformation parameters P_{NKG2} were published as well. More details can be found in [10].

3. RESULTS

The results are summarized here, more detailed results, parameters and coordinates can be found in [10].

3.1 Velocities of the NKG_RF03vel model

The velocities of the NKG_RF03vel model were compared to the ETRF2000 station velocities of the EPNC1785 solution. In the results, only stations in the land uplift area (meaning positive up velocity from the NKG_RF03vel) have been taken into account. Validity area of the NKG_RF03vel model is not explicitly given and therefore this constraint was applied to achieve more realistic statistics from the main usage area of the model. Outside the land uplift area the model may lack of geodetic data or experience far-field extrapolation or visualization related issues that have no physical meaning.

The precision (standard uncertainty) of the NKG_RF03vel velocities is below 0.5 mm/yr level in each velocity component and the accuracy (rms of the differences) is 0.45/0.20/0.91 mm/yr in North, East and up components compared to the ETRF2000 velocities of the EPNC1785. These and average velocity differences (horizontally 0.1-0.2 mm/yr, vertically 0.8 mm/yr) show that the vertical velocities of the NKG_RF03vel model are biased compared to the EPNC1785, see also Fig. 2 illustrating the velocity differences.

Fairly systematic differences mean that the consistency could be improved by an additional fit of the velocity field. After 7-parameter fit to the EPNC1785 velocities with 25 EPN stations the rms of differences is significantly improved to 0.34/0.18/0.42 mm/yr in North, East and up respectively, see Fig. 3. Considering the precision of the model, it is now well-aligned to the ETRF2000 velocities and possible deficiencies are mostly due to the original model itself. Some identified limitations in the NKG_RF03vel model are e.g. missing levelling data in Denmark and Baltic countries, weaknesses in the underlying GIA model and short time series at some GPS stations. Some of the larger velocity differences may be attributed to these reasons. However, below 0.5 mm/yr uncertainty level in modelled velocities is a very good result and proves that the NKG_RF03vel model is still performing mostly well.

3.2 Common NKG reference frame NKG_ETRF00

The original NKG2008 solution was aligned to the ITRF2008 at the epoch 2008.75 and the accuracy of the solution, by means of post-fit rms of fiducial sites, is 1, 1 and 3 mm in North, East and up components respectively. These coordinates were used to realize the common NKG_ETRF00 reference frame with the selected transformation (see Fig. 1). We estimated the accuracy of the NKG_ETRF00 by comparing the resulting coordinates with the EPNC1785 solution. We use this as a measure of the accuracy of the realized NKG_ETRF00 reference frame. It is important that the resulting reference frame is well-aligned to the official solution because it is a key factor to the access and sharing of data, i.e. reproducibility of the coordinates, in that frame.

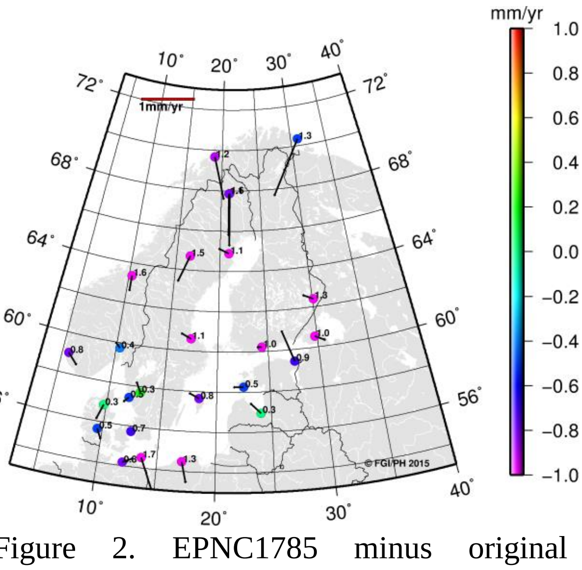


Figure 2. EPNC1785 minus original NKG_RF03vel velocities. Vectors show

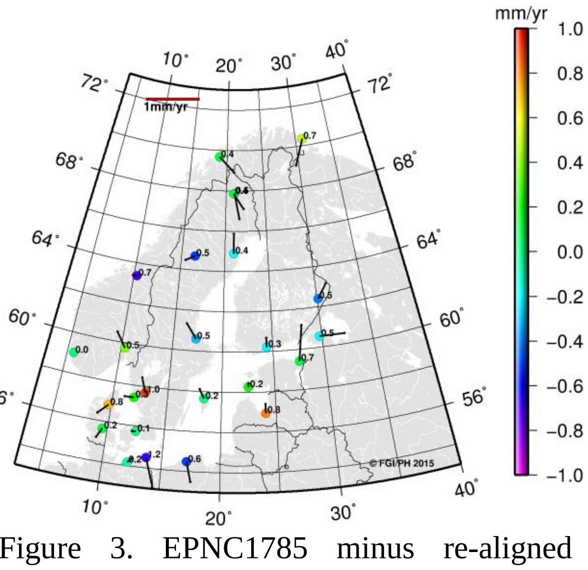


Figure 3. EPNC1785 minus re-aligned NKG_RF03vel_ETRF2000 velocities, i.e.

horizontal, coloured circles vertical and values next to the station 3D differences in mm/yr.

residuals of the re-alignment. Vectors show horizontal, coloured circles vertical and values next to the station 3D differences in mm/yr.

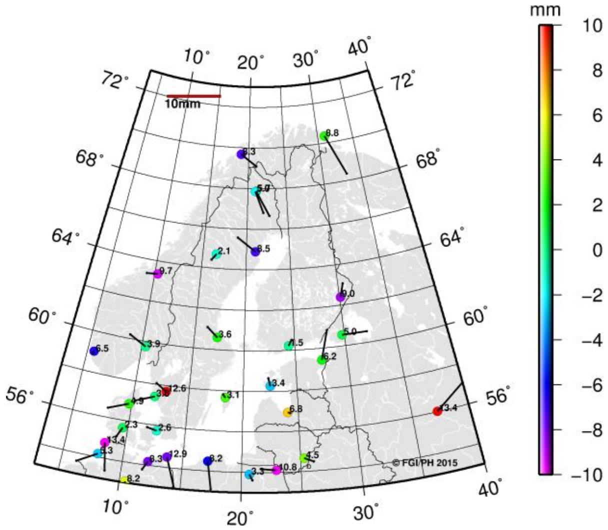


Figure 4. Coordinate differences NKG_ETRF00 minus EPNC1785. Vectors show horizontal, coloured circles vertical and values next to the station 3D differences in mm.

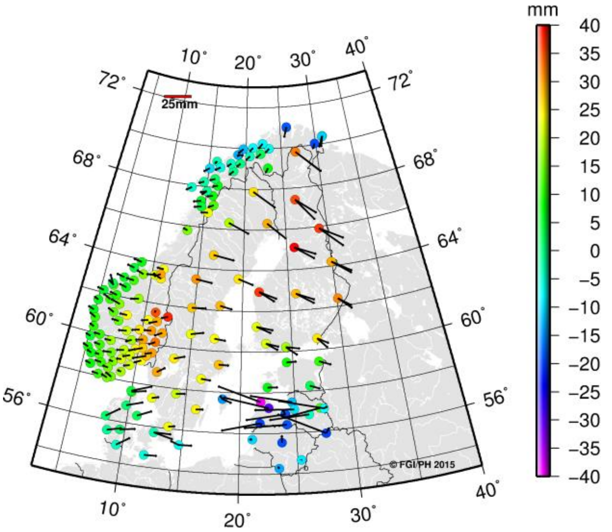


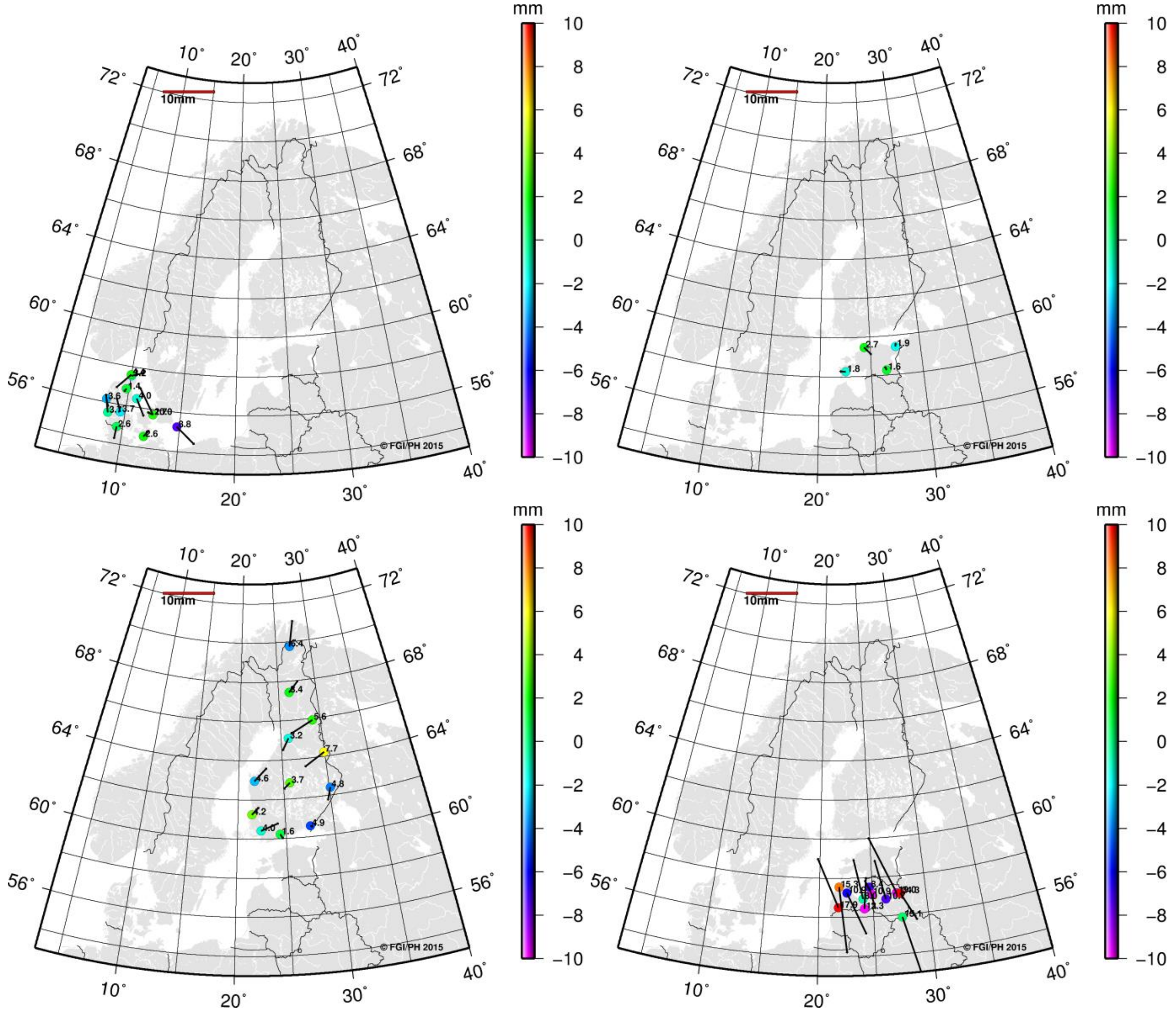
Figure 5. Coordinate difference NKG_ETRF00 minus national ETRS89 coordinates.

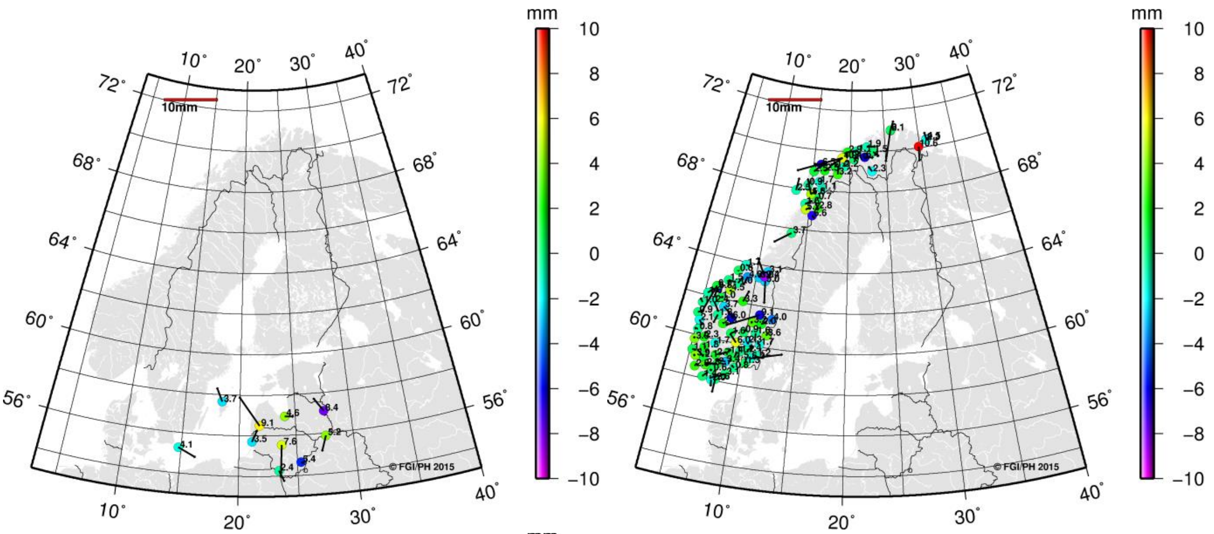
The accuracy of the NKG_ETRF00, by means of the rms of the coordinate differences, is 3.5/2.4/5.4 mm in North, East and up components. Consequently, the accuracy of the solution is not significantly degraded during the transformation. The result can be considered very good proving that our approach is suitable for the purpose. Figure 4 illustrates coordinate differences of the common reference frame realization. Most of the largest differences can be found outside the land uplift area (i.e. subsidence area) or close to it where the NKG_RF03vel model has its weakest points.

Figure 5 shows the differences of the NKG_ETRF00 and national ETRS89 coordinates, i.e. consistencies of the Nordic-Baltic ETRS89 realizations (through the NKG_ETRF00). The difference, by means of averages, is varying up to 4 cm in coordinate components being usually very systematic for each country. Some reasons are different reference epochs (intraplate deformations), different ETRFyy realizations and uncertainties in national realization campaigns. However, the consistency between the neighbouring countries is usually better, being mostly in the order of 1-2 centimetres. In cases where better consistency is needed, one can use the common reference frame NKG_ETRF00.

3.3 Transformations to national ETRS89 realizations

The NKG2008 transformation is performed country-wise and therefore transformation residuals can be used as an accuracy measure for accessing the national ETRS89 realizations from ITRF coordinates, i.e. national transformations. In case of the NKG2008 transformation the residuals reflect consistency of the input coordinates (both NKG2008 solution and national ETRS89 coordinates) and the intraplate model that is used to take care of the internal deformations. While the intraplate model NKG_RF03vel was shown to have an overall precision of 0.5 mm/yr level, most of the larger residuals should imply inconsistencies between the input coordinates.





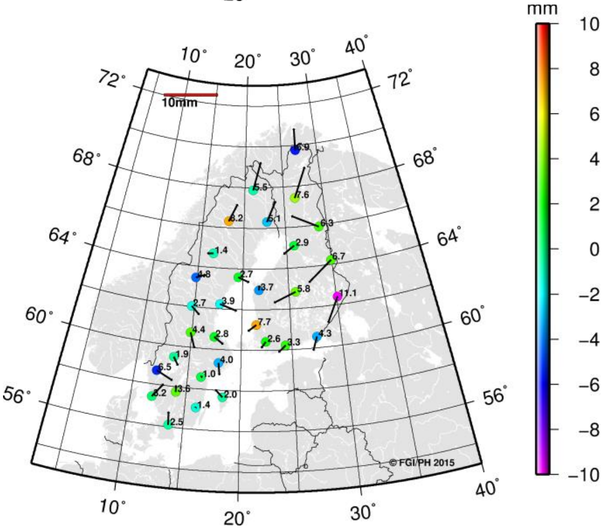


Figure 6. Transformation residuals for Nordic-Baltic countries, row-wise from top-left: Denmark, Estonia, Finland, Latvia, Lithuania, Norway and Sweden. Vectors show horizontal, coloured circles vertical and values next to the station 3D residuals in mm.

The rms of transformation residuals is some millimetres for most countries. This again proves that the NKG_RF03vel model is sufficient for correcting the intraplate deformations in the selected transformation approach. The residuals are illustrated country-wise in Fig. 6. The residuals are slightly larger for Latvia compared to the other countries which can be mostly attributed to the national ETRS89 coordinates. Latvian ETRS89 coordinates are based on EUREF.BAL'92 campaign that has an estimated accuracy of +/-2cm [14].

4. CONCLUSIONS

The ETRS89 is by definition fixed to the stable part of the Eurasian plate goal being minimized coordinate variations in time. Following this definition the coordinates of the national realizations have a clear epoch of validity, thus they are static over time (no velocities in the national realizations). However, the crust is deforming in the Nordic-Baltic region due to the postglacial rebound phenomenon that is not considered by this definition. Eventually, such a static reference frame becomes too imprecise (also too inaccurate) leading to the need for renewal of the reference frame. This is a huge task and instead, efforts towards semi-dynamic reference frames have been launched to prolong the lifetime of national reference frames.

We have developed a new NKG transformation procedure to access the Nordic/Baltic ETRS89 realizations from any ITRF solution at an arbitrary epoch. The transformation makes use of the de facto transformation by the EUREF with necessary amendments. The main addition is the model for crustal deformations taking care of the effect of the postglacial rebound. The residuals show that the national ETRS89 realizations can be accessed at a few millimetre level (1σ) for most of the Nordic/Baltic countries. This method can be seen as an option for implementing a semi-dynamic datum in the Nordic-Baltic countries.

The procedure includes a new common Nordic-Baltic reference frame as well. The common frame was aligned to the ETRF2000 at the epoch 2000.0, named as the NKG_ETRF00. Selection of the ETRF2000 as the underlying reference frame for the NKG_ETRF00 follows the recommendation of the EUREF TWG and with this choice the resulting common frame is close to the national ETRS89 coordinates as well. The chosen epoch 2000.0 is congruent with the national height systems (most of them being implementations of the EVRF2007), meaning the same "land uplift" epoch as the orthometric or normal heights in most Nordic/Baltic countries. The accuracy of NKG_ETRF00 reference frame realization is approximately 5 mm. Even if the Nordic/Baltic ETRS89 realizations are close to each other, 1-4 cm compared to the NKG_ETRF00, there might be applications requiring better consistency. The NKG_ETRF00 is useful in such applications. An example of such application is getting GNSS/levelling data to a consistent reference frame for verification of the common Nordic-Baltic geoid model.

Essential part of the transformation is the crustal deformation model NKG_RF03vel that takes care of intraplate deformations. The velocities of the original NKG_RF03vel model were re-aligned in this study to the ETRF2000 in order to enable accurate reference frame realization for the NKG_ETRF00 frame. The intraplate corrections to be applied in the transformation should be taken from the re-aligned NKG_RF03vel model. The alignment was implemented by introducing only transformation parameters without releasing a new model (e.g. grid files). Reasoning for this is that there were urgent needs for the updated transformation but a new improved model with amended geodetic data is already under way in the Nordic Geodetic Commission. Therefore it was not meaningful to produce a new model with old data. The work with new models and implementing them in the transformations will continue in the future.

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CONTACTS

Corresponding author
Mr. Pasi Häkli
Finnish Geospatial Research Institute (FGI),
National Land Survey of Finland
Geodeetinrinne 2
FI-02430 Masala
FINLAND
Email: pasi.hakli@nls.fi
Web site: www.fgi.fi