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Simplified transformations from ITRF2008/IGS08 to ETRS89 for maritime applications

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1   Summary

Simple transformations using the 7-parameter transformation model between ITRF2008 current epoch and ETRS 89 are requested.

This PM describes an approach to such transformations. The formulas are valid for maritime applications, but could also be used on land except for the central part of the Fennoscandian land uplift area.

Two sets of transformations have been defined – one for the stable part of Europe, excluding the Fennoscandian land uplift area and one for the Baltic Sea. Yearly parameters have been estimated for year 2012-2015.

The general accuracy of the transformation formulas is 1-2 cm in the chosen ETRF representing ETRS 89, but national differences as well as some special areas like the Norwegian fjords and eastern Mediterranean get considerably larger differences. Maps with residuals give a hint of these areas.

The next realization of ITRS, ITRF2013, is expected to be released 2014 and one could guess that the EPN densification of ITRF2013/IGS13 will be available 2015. After that, new transformations have to be developed based on ITRF2013/IGS13.

2   Introduction

Positions determined by the GNSS method Precise Point Positioning (PPP) are in the same reference frame as the orbits, i.e. usually a realization of ITRS[1], e.g. ITRF[2]yy, IGS[3]yy or WGS84[4], where "yy" represents the year of the realization. The coordinates change with time in ITRFyy, because of the plate tectonics – see *Figure 1*. Hence, the determined coordinates are given in the epoch of the observations.

Such ITRF coordinates could also be achieved e.g. from relative measurements from stations in the IGS-network.

For practical applications like mapping and referencing spatial data, a static system/frame, which does not change with time, is desired. For this purpose ETRS 89 has been developed for Europe. ETRS 89 coincide with ITRS at epoch 1989.0.

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[1] International Terrestrial Reference System

[2] International Terrestrial Reference Frame

[3] International GNSS Service, IGS has own realizations of the ITRF

[4] Worls Geodetic System 1984, used by GPS

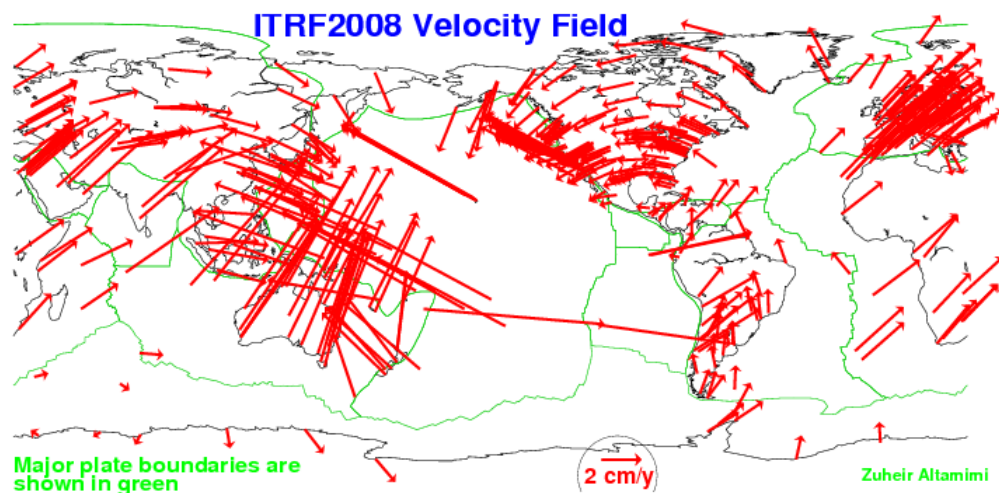WGS84 is connected to ITRS since 1994 and the latest update (February 2012) is aligned to ITRF2008.

Figure 1: The plate tectonics described by the ITRF2008 velocity field.

In [Boucher, Altamimi 2011] the official EUREF-transformation from ITRFyy epoch yyyy.y to ETRFxx epoch yyyy.y is described. This transformation does not take the internal velocities within the European plate into account, i.e. the epoch yyyy.y remains. This means that stations close to the land uplift maximum will get an error larger than 1 dm in height when transforming from a recent epoch (2012) in ITRF to ETRS 89, compared to the Swedish or Finnish realization of ETRS 89.

For the Nordic area transformations from ITRF 2000 to the national ETRS 89 realizations of Sweden, Norway, Denmark and Finland have been developed [Nørbech et. al. 2006]. The transformation from ITRF 2005 current epoch to the Swedish ETRS 89 realization, SWEREF 99, is described in [Jivall, Kempe 2009]. Both tranformations use grid files for interpolation of the deformations caused by the postglacial rebound. The vertical part of this model is shown in *Figure 2*.

For some applications the official EUREF-transformation according to [Boucher, Altamimi 2011] without taking internal deformations into account is not sufficient and at the same time it is not possible to handle a gridded land uplift model. The request from e.g. maritime users is to use the 7-parameter similarity transformation (3D-Helmert-tranformation), which easily could be implemented. To account for the plate tectonics and the land uplift, different parameters could be solved for different years.

An approximate transformation from ITRF2005 current epoch to EUREF89/ETRS89 in Norway for offshore use has also been developed

[Nørbech T, Kierulf H 2007]. This transformation is based on a 7-parameter transformation in epoch 2007.0. To account for the current epoch this transformation is preceded by a time dependent rotation. Unfortunately this step could not easily be implemented in many GNSS-softwares, which in some cases have led to that the reduction of the epoch not has been used.
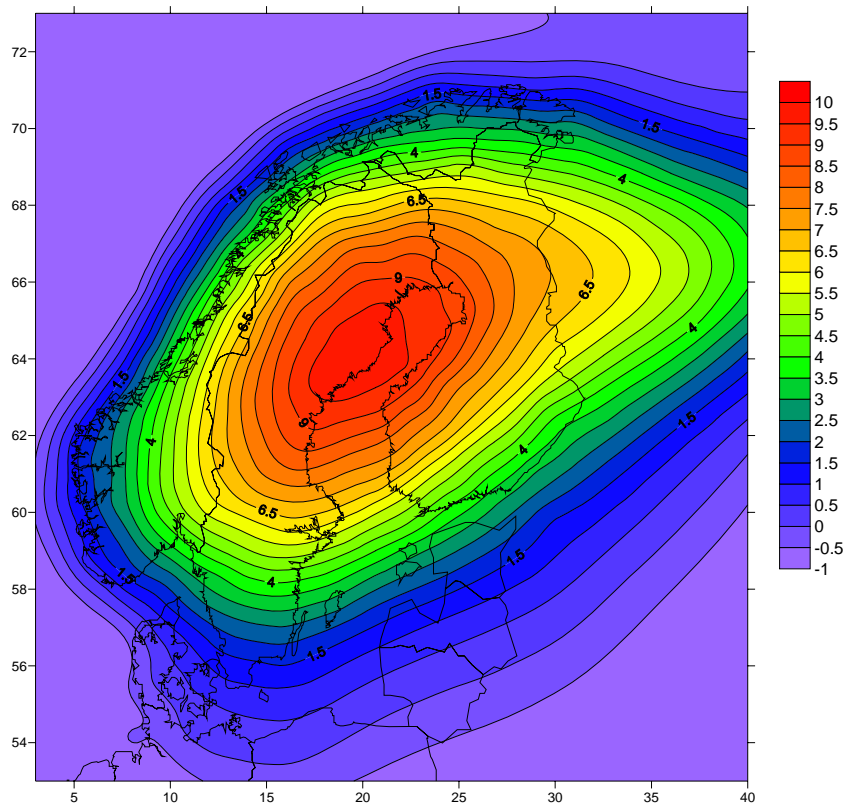

Figure 2: The vertical land uplift model NKG2005LU(ABS).

3 ITRF 2008 and IGS 08

ITRF2008 is today (2012) the latest realization of ITRS. It was released May 2010 and the IGS-version of it, IGS08, was introduced into IGS- and EPN-processing in GPS-week 1632 (April 2011). This means that the IGS-products (orbits and clocks used e.g. for PPP) from this date are in IGS08.

IGS has adjusted each ITRFyy to be consistent with the GNSS-solutions. For the latest two ITRFs (ITRF2005) and ITRF2008) adjustments have also been made for the new antenna tables that have been introduced. The GPS-component for ITRF2008 has been processed with antenna models in the table igs05.atx, but when introducing the new frame into the IGS- and EPN-processing, a new updated antenna table, igs08.atx, is used. Stations with an

updated antenna model have also got updated coordinates in IGS08 compared to ITRF2008.

In other words, IGS08 - the IGS-version of ITRF2008 - is fully consistent with the latest official antenna models (igs08.atx). When performing PPP with IGS-products and using antenna models from igs08.atx, the result will be in IGS08.

IGS08 does just have coordinates for IGS-stations fulfilling certain criteria on data span and number of discontinuities. The number of stations around the Baltic Sea, which is affected by the post glacial rebound, was not sufficient for estimating transformation parameters in this area. Therefore, we decided to wait for the EPN densification of IGS08, here denoted EPN_A_IGS08, but also called IGS08_C1680. This solution was published in November 2012 and is based on EPN-solutions up to GPS-week 1680 (March 2012) [Kenyeres 2012]. The plan is that this solution will be followed by successive solutions each 15 weeks, just as was the case for the EPN-densification of ITRF2005. For the computation of EPN_A_IGS08, station wise corrections for the difference between igs05.atx and igs08.atx have been applied for solutions before GPS-week 1632.

EPN_A_IGS08 consists of coordinates and velocities for so called class A-stations. These are stations that could be used as reference stations for ETRS 89 densifications. They should have at least 2 years of data and a velocity uncertainty less than 0.5 mm/yr in all components. Some stations have more than one set of coordinates. The reason for this is usually equipment change at the station that has introduced a shift into the coordinate time series. The most recent interval for each station has been used in this study.

The next realization of ITRS will be ITRF2013, expected to be released 2014 [Altamimi 2012].

4   National ETRS 89 coordinates and ETRFxx based on EPN-solutions

The ETRS 89 is based of ITRS and is tied to the stable part of Europe. ETRS 89 coincide with ITRS at epoch 1989.0. For each ITRFyy there exist a corresponding ETRFyy, but for the last two ITRFs (ITRF2005 and ITRF2008), Euref Technical Working group recommends the use of ETRF2000 as a conventional frame, i.e. ETRF2000(R08) is the corresponding ETRF to ITRF2008.

The national realizations of ETRS 89 are based on different ITRFs/ETRFs and have been established during almost a 20 years period. Before the

conventional frame ETRF2000 was introduced, there was often a shift between the ETRFs that could be up to a couple of cm in the more peripheral parts of Europe. In addition to this, the epoch of the observation campaign is important for areas which do not belong to the stable part of Europe (e.g. Fennoscandia). Furthermore, some countries have updated their coordinates when the old ones have got obsolete, e.g. by antenna replacement, others have not.

This means that the national ETRS 89 realizations do not form a fully homogeneous system, although it for many practical applications could be considered as one system. Furthermore, many national frames are not defined by any EPN-sites.

The IGSyy/ITRFyy solutions from the processing of the EPN-network, e.g. EPN_A_IGS08, could of course also be transformed with the EUREF-transformations [Boucher, Altamimi 2011] to the conventional frame ETRF2000(R08).

ETRF2000(R08), or any other ETRF based on EPN-solutions, is a more homogenous and updated system with a better coverage than the combination of the national realizations. For this reason, ETRF derived from EPN-solutions is a better choice to be used for the estimation of transformation parameters. However in the end, ETRS 89 is for many users usually understood as their national realization. Hence it is important to choose the ETRF-solution(s), for the estimation of transformation parameters, in such a way that the differences to the national realizations are small.

National ETRS 89 coordinates for EPN-stations are available on the EPN web, if such exist and have been submitted to EUREF. These are used for the initiative "Monitoring of official national ETRF coordinates on EPN web" [Brockmann 2009]. For the present study national coordinates were achieved directly from Elmar Brockmann.

It turned out quite soon that there will be two areas with different sets of transformations – one for central Europe and one for the Baltic Sea. For central Europe the median epoch of the available national realizations is 2007 (if disregarding realizations claiming that the epoch is 1989.0, which probably either is a misunderstanding or refer to old and bad data). Many of the realizations are also based on the conventional frame ETRF2000. Hence EPN_A_IGS08 transformed to ETRF2000 epoch 2007.0 was chosen to represent the national ETRS 89 in central Europe.

The Swedish and Finnish national ETRS 89 realizations, which have the longest coast line along the Baltic Sea and are most affected by the post glacial rebound, are based on ETRF97 epoch 1999.5 and ETRF96 epoch

1997.0, respectively. ETRF97 epoch 1998.5 was chosen to represent ETRS 89 in the area around the Baltic Sea.

The differences between the national realizations and ETRF2000 epoch 2007.0/ETRF97 epoch 1998.5 are shown in *Figure 3 - Figure 6*. Stations with turquoise vectors are just included as control. In case of e.g. METS in *Figure 6*, the official national coordinates have not been updated for the antenna replacement in 2010. The official ETRS 89 for Riga have quite large difference in height compared to ETRF97 epoch 1998.5. One part of the explanation is that the Latvian ETRS 89 is based on ETRF2000, which has c. 1-2 cm difference in height compared to ETRF97 in this area.

Figure 3: Horizontal differences; EPN_A_IGS08 transformed to ETRF2000(R08) epoch 2007.0 minus official national ETRS 89 coordinates, excluding the Fennoscandian land uplift area.
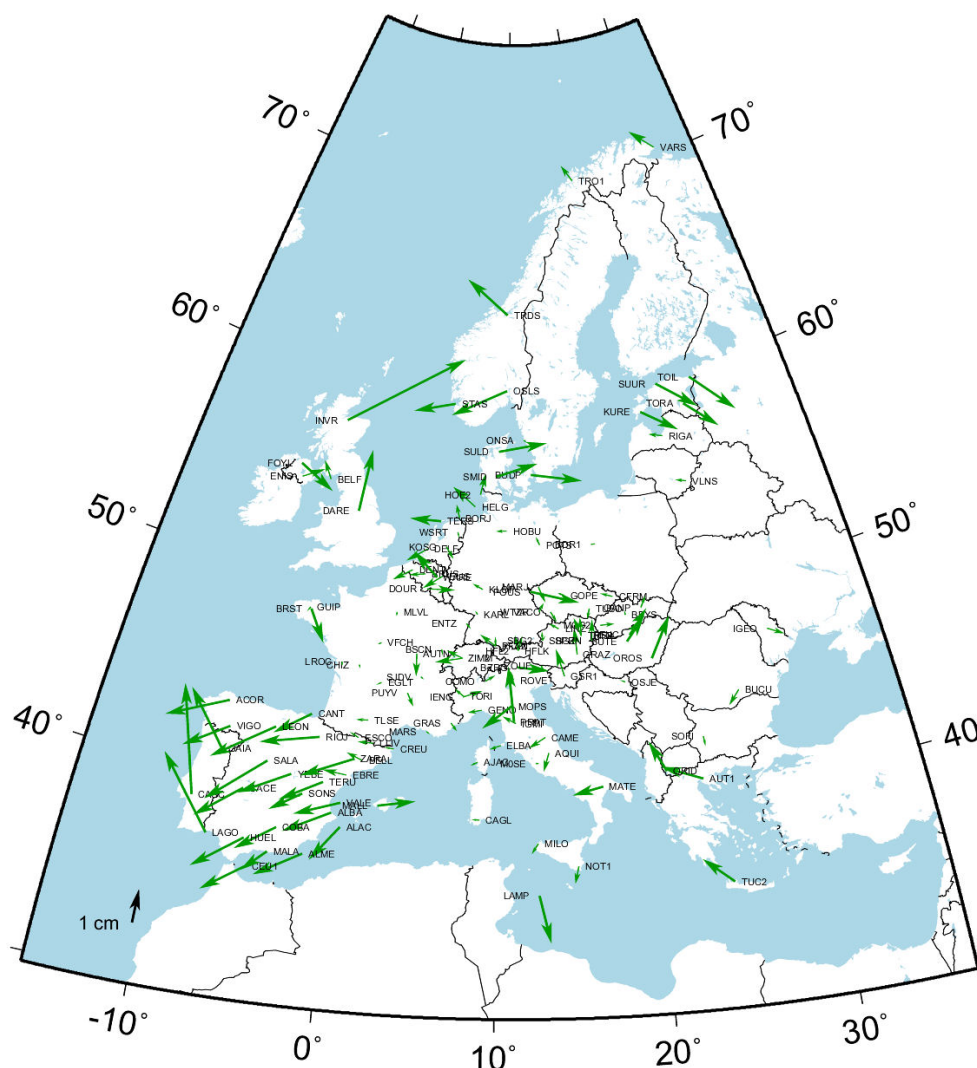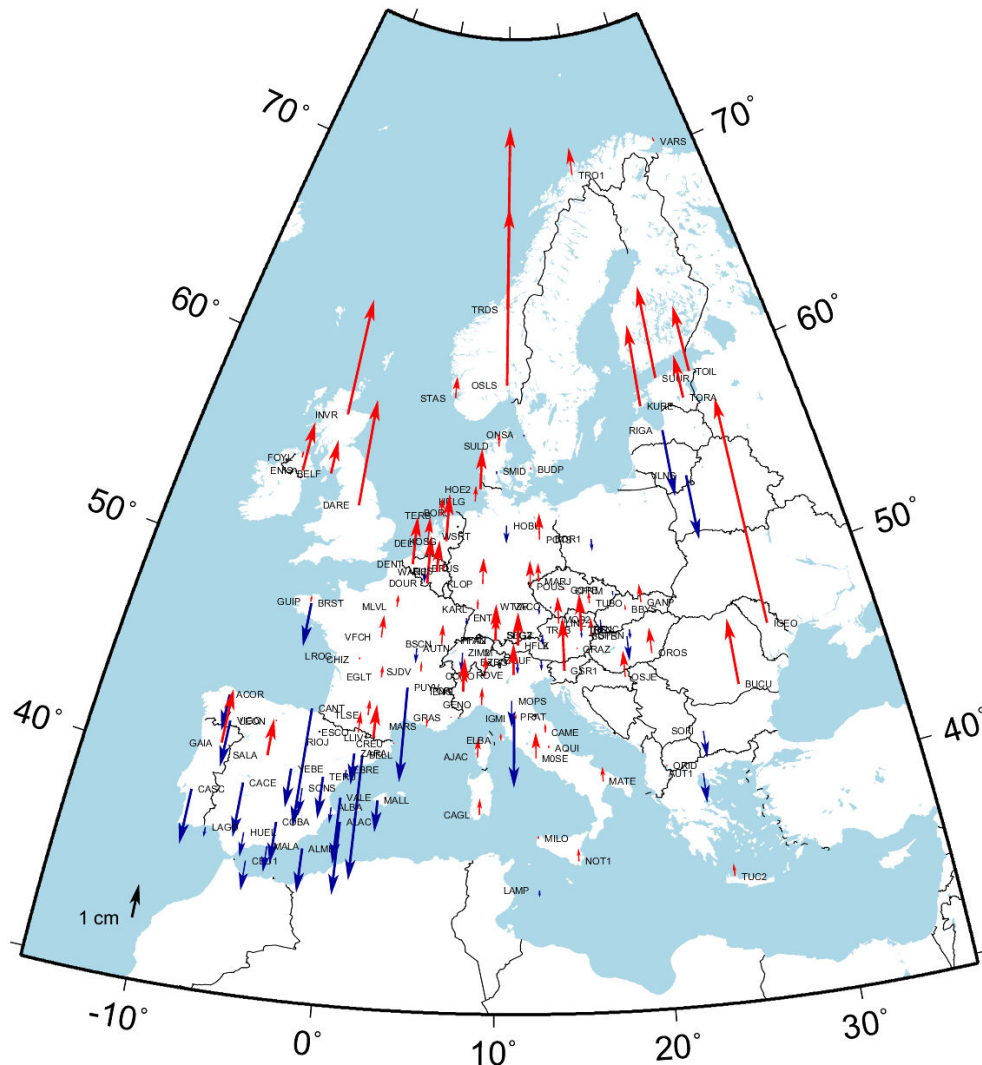
Figure 4: Vertical differences; EPN_A_IGS08 transformed to ETRF2000(R08) epoch 2007.0 minus official national ETRS 89 coordinates, excluding the Fennoscandian land uplift area.
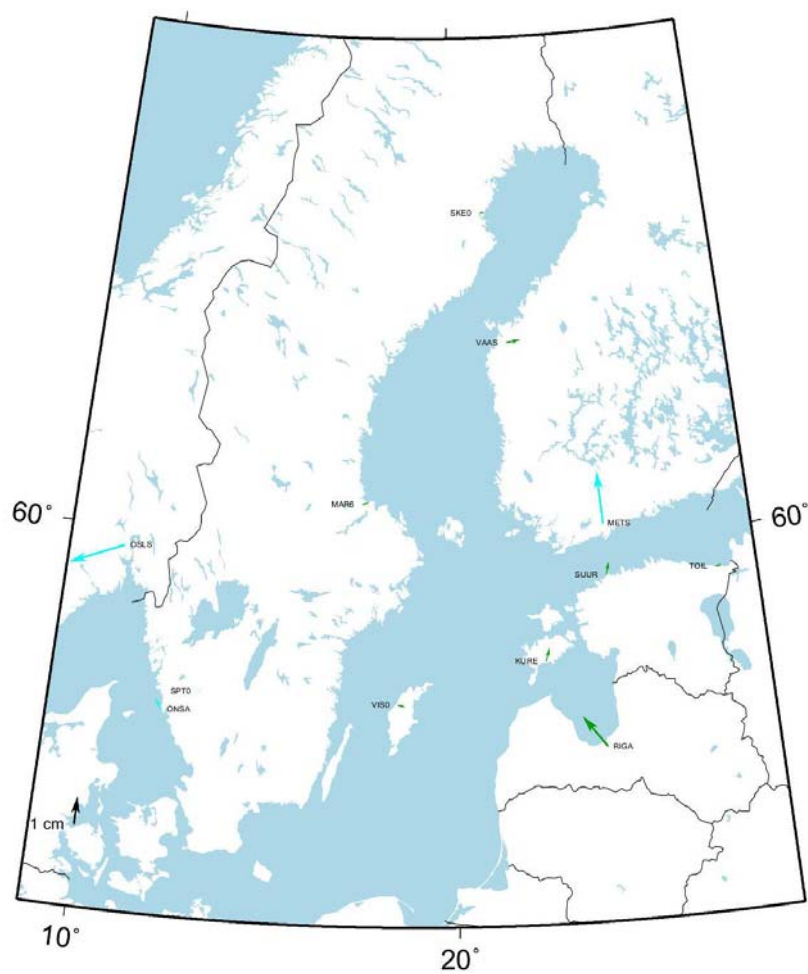
Figure 5: Horizontal differences; EPN_A_IGS08 transformed to ETRF97(R08) epoch 1998.5 minus official national ETRS 89 coordinates, for the Baltic Sea.
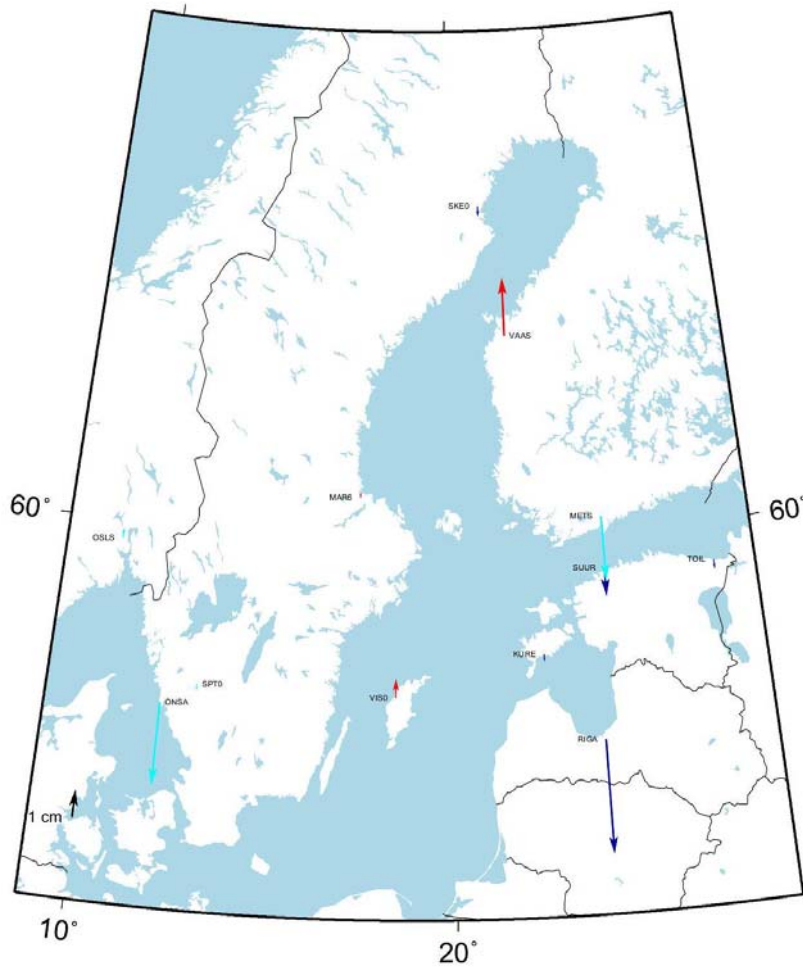
Figure 6: Vertical differences; EPN_A_IGS08 transformed to ETRF97(R08) epoch 1998.5 minus official national ETRS 89 coordinates, for the Baltic Sea.

5 Basic model for the transformations

The request was to use the 7-parameter similarity transformation formula, i.e. a 3D-Helmert transformation. This type of transformation could easily be implemented in many applications. The formulas are found in section 8.

The transformations are defined from ITRF2008 to ETRS 89.

The EPN-densified IGS08-solution (EPN_A_IGS08) including coordinates and velocities represents ITRF2008. This solution transformed to ETRS 89 according to the formulas and parameters in [Boucher, Altamimi 2011] represents ETRS 89 (ETRF xx, epoch yyyy.y). The xx and yyyy.y are dependent on the area, i.e. what is the dominant ETRS89-realization in the area (see section 4).

Yearly parameters have been solved, as ITRF changes with the plate tectonic (2-3 cm/yr), i.e. the maximum error dependent on the epoch will be 1,5 cm in horizontal – see *Figure 1*. The transformations in each area are described in *Table 1*. Coordinates in each epoch have been achieved by propagating the original coordinates (which are given in epoch 2005.0) with the velocities for each station.

Yearly epochs are chosen in the middle of the year as the main part of the measurements is believed to be made during the summer.

The next realization of ITRS, ITRF2013, is expected to be released 2014 and one could guess that the EPN densification of ITRF2013/IGS13 will be available 2015. Transformation parameters are estimated up to epoch 2015.5. After that new transformations have to be developed based on ITRF2013/IGS13.

Table 1: From and to-system for the different 7-parameter transformations in an area. ETRFxx and the epoch yyyy.y are dependent on the area.

From-system	Epoch	To-system	Epoch
EPN_A_IGS08	2012.5	ETRFxx	yyyy.y
EPN_A_IGS08	2013.5	ETRFxx	yyyy.y
EPN_A_IGS08	2014.5	ETRFxx	yyyy.y
EPN_A_IGS08	2015.5	ETRFxx	yyyy.y

6   Transformation for areas outside the Fennoscandian land uplift

ETRF2000 epoch 2007.0 represents ETRS 89 in the area.

This area includes whole Europe besides the areas affected by the Fennoscandian land uplift. Also the Norwegian coast is covered as the land uplift there is close to zero. The fjords are however affected by land uplift and will get larger residuals in this transformation. The eastern part of the Mediterranean Sea does have large horizontal velocities with respect to the European plate, hence stations there do not fit so well.

The residuals for the transformation in epoch 2012.5 and 2015.5 are shown in *Figure 7- Figure 10*. Turquoise arrows represent stations that have been excluded from the fit, i.e. they are not contributing to the determination of the parameters, but the arrows show the differences between defined and transformed ETRS 89 coordinates. Stations with residuals > 20 mm in any

component were automatically rejected from the fit. The residuals give a picture of what accuracy could be expected when using the transformation in different parts of Europe.

Figure 7: ITRF2008, epoch 2012.5 to ETRF2000 epoch 2007, horizontal residuals in the Helmert-transformation.

The differences to official national coordinates are given by subtracting the residuals in the Helmert-fits (in this and the next section) from the comparisons between ETRFxx epoch yyyy.y to the official national coordinates (in previous section).

Figure 8: ITRF2008, epoch 2012.5 to ETRF2000 epoch 2007, vertical residuals in the Helmert-transformation. Red arrows are positive residuals and blue are negative.

In general, both the horizontal and vertical fit is on the 1 cm level in epoch 2012.5, but there are some exceptions.

The horizontal residuals are quite large in the eastern part of the Mediterranean but the vertical look OK. Also the Norwegian stations fit well to the European transformation where ETRS 89 is defined in in epoch 2007.0. The Norwegian stations Oslo (OSLS) and Trondheim (TRDS), both located in fjords and affected by land uplift, have residuals of 22 mm and 14 mm in height in this Helmert fit, but when compared to the Norwegian national ETRS 89 realization (epoch 1997), the differences would be 74 mm for Oslo and 67 mm for Trondheim (the transformed coordinates are higher). The

differences get larger when ITRF2008 is extrapolated to epoch 2015.5 and more stations are excluded– see *Figure 9* and *Figure 10*.

The general fit for epoch 2015.5 is on 1-2 cm level and but e.g. stations at the Canaries and the Azores have 3 cm difference in east. Trondheim differs 23 mm and Oslo 35 mm in height.
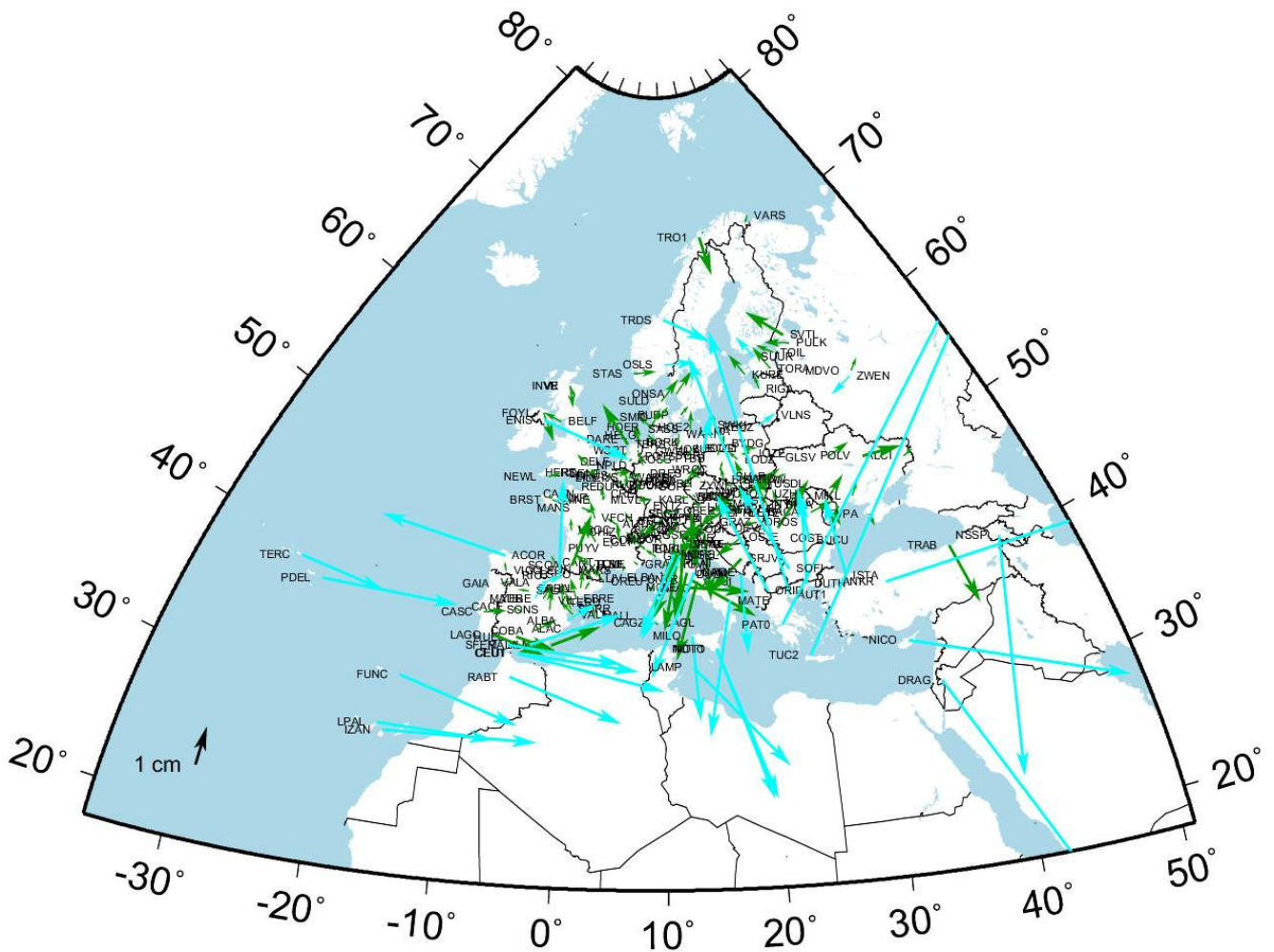

Figure 9 : ITRF208, epoch 2015.5 to ETRF2000 epoch 2007, horizontal residuals in the Helmert-transformation.
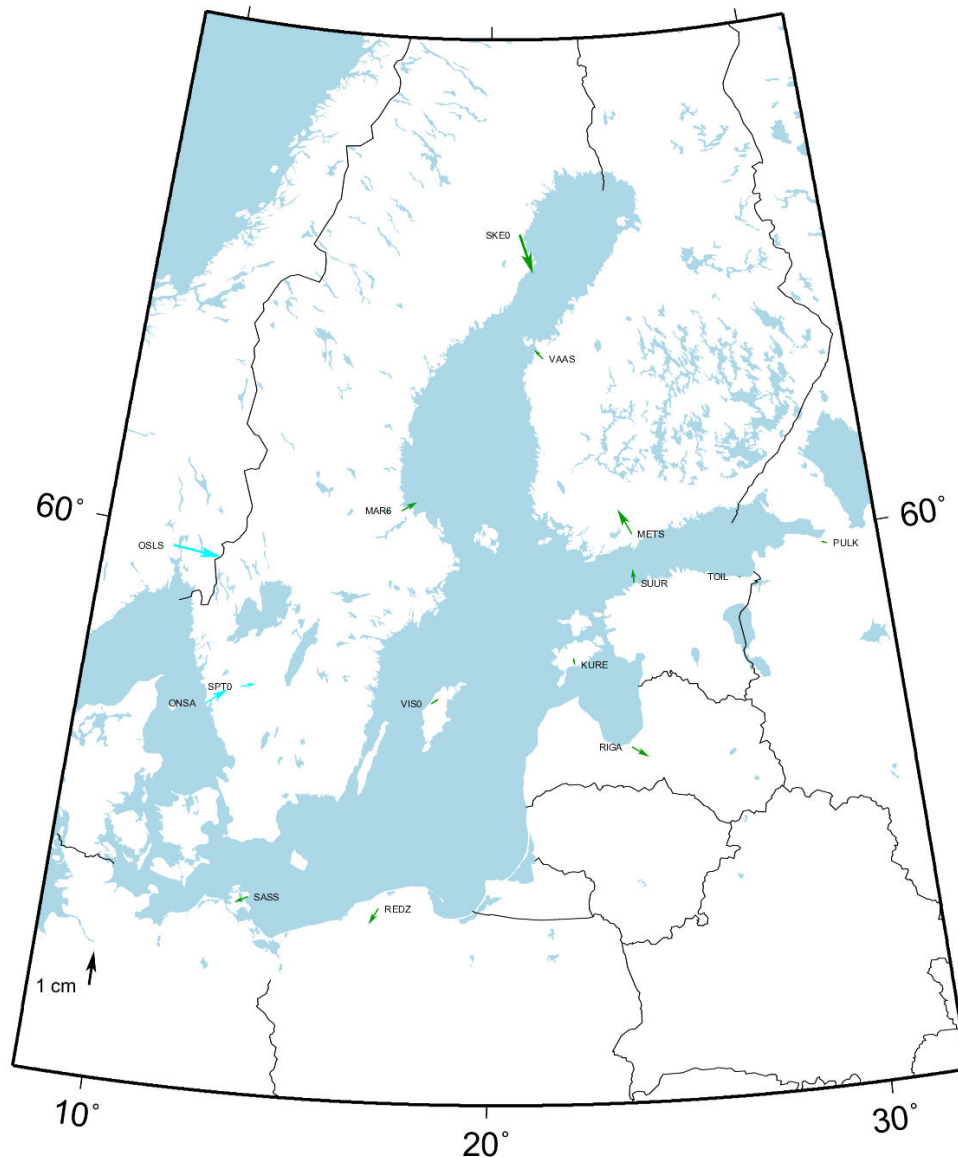
Figure 10: ITRF2008, epoch 2015.5 to ETRF2000 epoch 2007, vertical residuals in the Helmert-transformation.

7 Transformation for the Baltic Sea and the lake Vänern

A special set of transformations were developed for the Baltic Sea. The reason for this is that this area is affected by the post glacial rebound. The transformations work also for the southern part of Sweden including lake Vänern, but not for other parts of Fennoscandia or Finland.

ETRF97 epoch 1998.5 represents ETRS 89 in the area.

Residuals from the 7-parameter transformations for epoch 2012.5 and 2015.5 are found in *Figure 11 - Figure 14.*

Figure 11: ITRF2008, epoch 2012.5 to ETRF97 epoch 1998.5, horizontal residuals in the Helmert-transformation.

Onsala (ONSA), Borås (SPT0) and Oslo (OSLS) are just included in the plots as test points. The purpose was to get an impression of what happens at Lake Vänern. In addition, a separate 7-parameter fit was made for Lake Vänern using OSLS, SPT0, ONSA, MAR6 and VIS0 as fitting points. A number of points around lake Vänern were transformed with both transformation formulas and the differences were below 1 cm in both height and horizontal for epoch 2012.5 and 2015.5. The conclusion is that the transformation for the Baltic sea also works for lake Vänern and no separate transformation is needed.
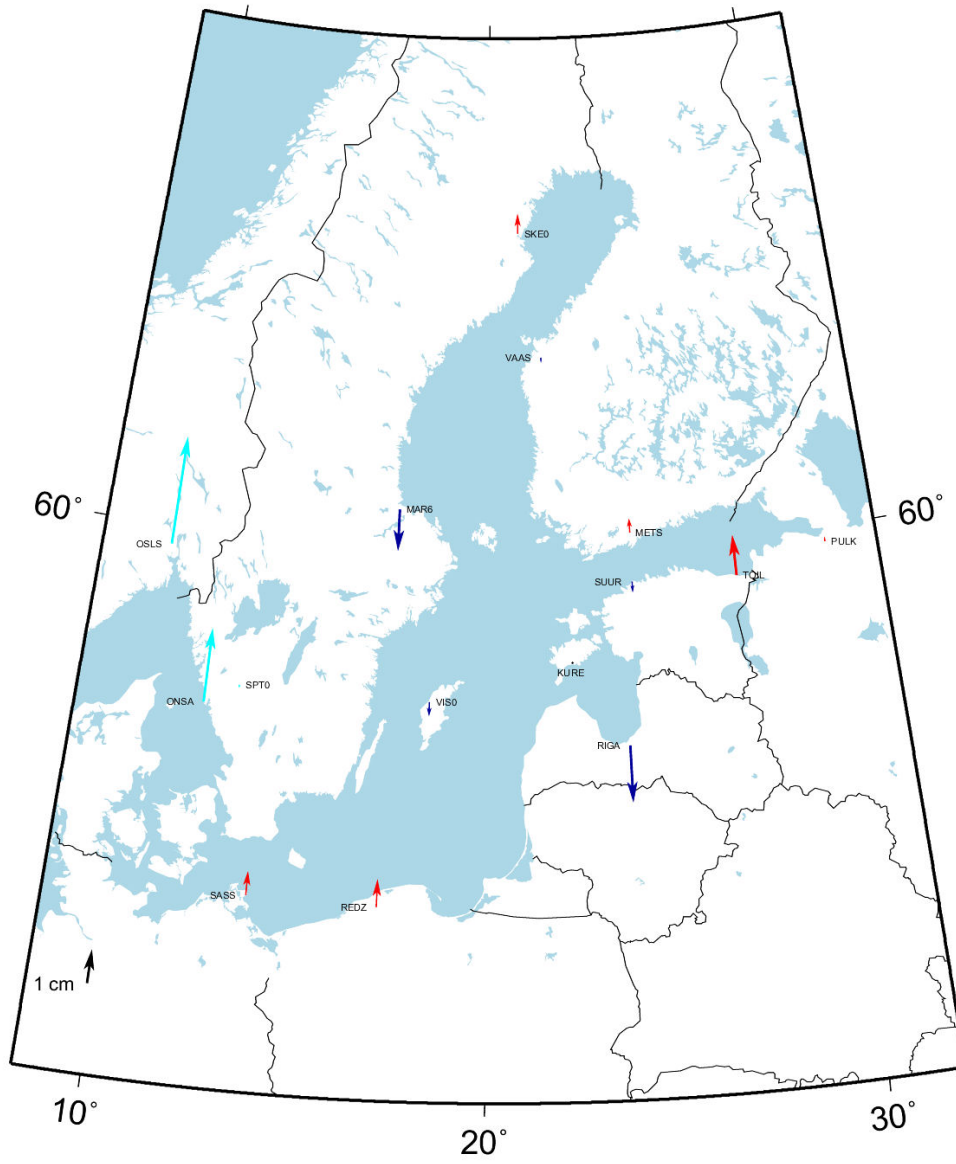
Figure 12: ITRF208, epoch 2012.5 to ETRF97 epoch 1998.5, vertical residuals in the Helmert-transformation.
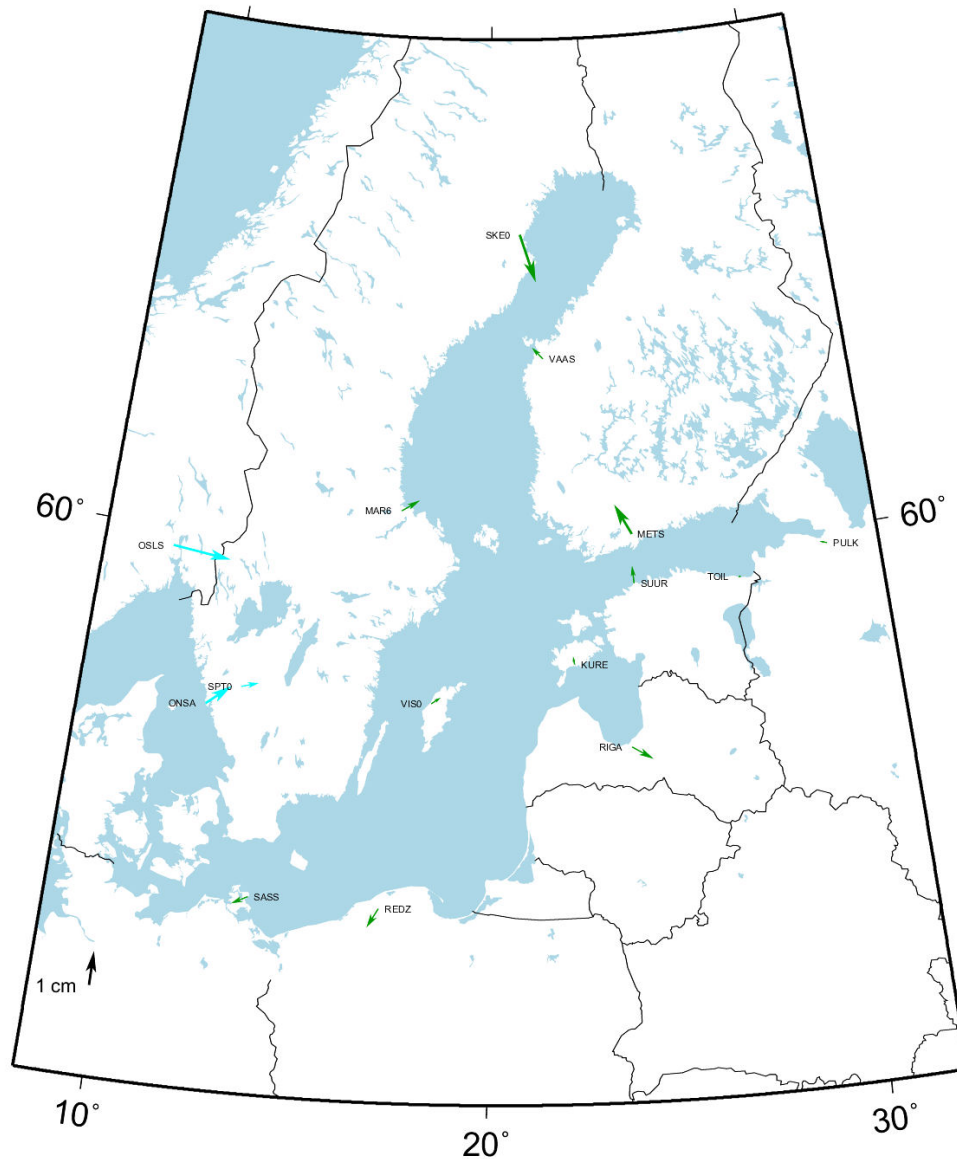
Figure 13: ITRF2008, epoch 2015.5 to ETRF97 epoch 1998.5, horizontal residuals in the Helmert-transformation.

The residuals grow of course larger with the later epoch 2015.5. The vertical residual at Mårtsbo (MAR6) and the horizontal residual at Skellefteå (SKE0) are both 15 mm for epoch 2015.5.
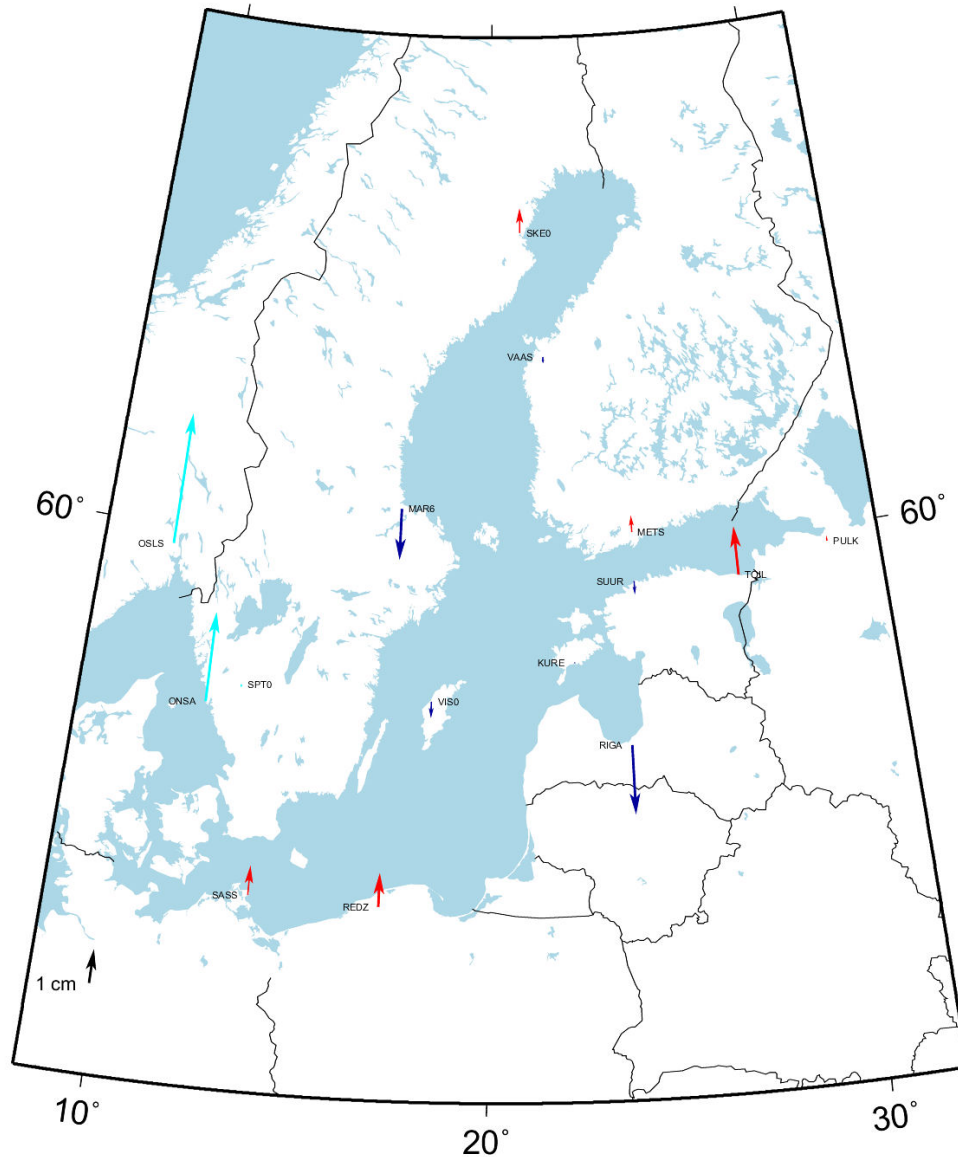
Figure 14: ITRF2008, epoch 2015.5 to ETRF97 epoch 1998.5, vertical residuals in the Helmert-transformation.

8   Transformation formulas and parameters

The 7-parameter similarity transformation, which also is called 3D-Helmert transformation, is used for the transformations. The parameters have been determined using formulas with the full rotation matrix (formula 1 and 2), but could also be used together with the linearized version (formula 1 and 3) without losing any precision as the rotations are small.

There are two sets of transformation parameters, one for central Europe including the British Islands and the sea outside Norway – see table *Table 2*- and another for the Baltic Sea – see *Table 3*. Parameters have been estimated for the following epochs; 2012.5, 2013.5, 2014.5 and 2015.5, to be used for each corresponding year.

The residual plots from the estimation of the parameters – see section 6 and 7 – give an idea about the accuracy of the transformations.

$$
\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{ETRS\,89} = \begin{pmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{pmatrix} + (1+\delta)\ \mathbf{R} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_{ITRF} \tag{1}
$$

$$
\mathbf{R} = \mathbf{R}_Z \mathbf{R}_Y \mathbf{R}_X = \begin{pmatrix} \cos\omega_Z & \sin\omega_Z & 0 \\ -\sin\omega_Z & \cos\omega_Z & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\omega_Y & 0 & -\sin\omega_Y \\ 0 & 1 & 0 \\ \sin\omega_Y & 0 & \cos\omega_Y \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\omega_X & \sin\omega_X \\ 0 & -\sin\omega_X & \cos\omega_X \end{pmatrix} \tag{2}
$$

$$
\mathbf{R} = \mathbf{R}_Z \mathbf{R}_Y \mathbf{R}_X = \begin{pmatrix} 1 & \omega_Z & -\omega_Y \\ -\omega_Z & 1 & \omega_X \\ \omega_Y & -\omega_X & 1 \end{pmatrix} \tag{3}
$$

Table 2: Parameters for different epochs to be used in central Europe, the British Islands and outside the Norwegian coast.

Parameter	2012.5	2013.5	2014.5	2015.5
ΔX (m)	0.07567	0.07955	0.07790	0.07451
ΔY (m)	0.04969	0.05601	0.05739	0.05471
ΔZ (m)	-0.09022	-0.09665	-0.10409	-0.10463
ω_x (mas)	-2.141	-2.403	-2.431	-2.419
ω_Y (mas)	-10.840	-11.139	-11.534	-12.132
ω_Z (mas)	18.115	18.999	19.949	20.697
δ (ppb)	1.66	1.80	2.80	3.22

Table 3: Parameters for different epochs to be used in the Baltic Sea.

Parameter	2012.5	2013.5	2014.5	2015.5
ΔX (m)	0.67678	0.72188	0.76705	0.81244
ΔY (m)	0.65495	0.69856	0.74221	0.78540
ΔZ (m)	-0.52827	-0.56039	-0.59261	-0.62483
ω_x (mas)	-22.742	-24.227	-25.716	-27.196
ω_Y (mas)	12.667	13.911	15.158	16.411
ω_Z (mas)	22.704	23.892	25.075	26.245
Δ (ppb)	-10.70	-11.68	-12.65	-13.62

Note the definition of the rotations in formula 2 and 3 and change sign if necessary. The rotations need also to be converted to radians by multiplication with the following factor:

$$\frac{0.001 \cdot \pi}{3600 \cdot 180}$$

9 Test example

Table 4: Coordinates for testing the implementation of the transformation parameters.

Reference Frame	X	Y	Z
ITRF2008 epoch 2012.5	3565285.0000	855949.0000	5201383.0000
ETRS 89, central Europe (2012.5)	3565285.4301	855948.6840	5201382.7399
ETRS 89, Baltic Sea (2012.5)	3565285.4134	855948.6799	5201382.7294
ITRF2008 epoch 2013.5	3565285.0000	855949.0000	5201383.0000
ETRS 89, central Europe (2013.5)	3565285.4457	855948.6686	5201382.7301
ETRS 89, Baltic Sea (2013.5)	3565285.4286	855948.6647	5201382.7198
ITRF2008 epoch 2014.5	3565285.0000	855949.0000	5201383.0000
ETRS 89, central Europe (2014.5)	3565285.4615	855948.6537	5201382.7212
ETRS 89, Baltic Sea (2014.5)	3565285.4438	855948.6495	5201382.7103
ITRF2008 epoch 2015.5	3565285.0000	855949.0000	5201383.0000
ETRS 89, central Europe (2015.5)	3565285.4778	855948.6387	5201382.7125
ETRS 89, Baltic Sea (2015.5)	3565285.4590	855948.6343	5201382.7008

In order to test the implementation of the transformations, a test example has been prepared – see *Table 4*. Note that the ITRF2008-coordinates are the same for both epochs, which means that it is not the same point. The points are approximately in the middle between Skåne and Rügen, so in principle both transformations would be applicable. The difference between the two transformations in epoch 2012.5 is 8 mm in horizontal and 18 mm in height, mainly reflecting the difference between ETRF2000 epoch 2007 and ETRF97 epoch 1998.5.

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