EPN Reference Frame Alignment: Consistency of the Station Positions

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Abstract

In this paper, different approaches to tie a GNSS network to a conventional reference frame, using minimal constraints have been investigated. We created and analysed regional (European) and global cumulative solutions, used both the IGS05 and ITRF2005 as datum, tested different sets of transformation parameters in the minimal constraints, and used different sets of reference stations for the datum definition.

Due to the correlation of the Helmert parameters in a regional network, each of the standard geocentric approaches originally dedicated to tie global networks to a reference frame, has shown deficiencies.

It was demonstrated that regional solutions can show biases (up to the cm-level) with respect to each other and we conclude that at the regional level, the choice between the IGS05 or ITRF2005, the selection of the reference station set and the number of parameters used to apply the minimal constraints is crucial. In comparison, global solutions are much more stable and agree within the 2 mm-level.

1. Introduction

EUREF, the “Reference Frame Sub-Commission for Europe” is part of Sub-Commission 1.3, “Regional Reference Frames”, under Commission 1 of the IAG (International Association of Geodesy). The main goal of EUREF is to maintain and provide access to the European Terrestrial Reference System (ETRS89) through the EUREF Permanent Network (EPN). The EPN covers the European continent with more than 200 continuously observing dual frequency GPS and GPS/GLONASS receivers (Bruyninx et al. 2004). One of the EPN products consists of weekly coordinate solutions in the SINEX (Blewitt et al. 1994) format, derived from the combination of 16 overlapping sub-network solutions computed by different analysis centres.

At the establishment of the EPN in 1996, it was decided that the GNSS data analysis would be performed on a regional (European) level without stations outside Europe (such as the global stations from the International GNSS Service (IGS)). However, today with the improving computing facilities and GNSS data analysis software, it has become feasible to perform a global analysis. Therefore, as a preparation for the EPN reprocessing, we analyzed and compared the classical regional approach to a global one, where IGS stations uniformly covering the globe were added to the processed EPN network.

Historically, two methods were used to express the weekly EPN coordinate solutions in the successive realizations of the ITRF (International Terrestrial Reference Frame). Before GPS week 1303 (Dec 2004), coordinates of selected stations were constrained to the values of the conventional reference frame. Today, the alignment of the solutions is done using a Helmert transformation in a minimal constraint approach. The advantage of minimal constraints is that they preserve the original characteristics of the solution (Altamimi 2003) and do not deform the original network geometry.

Two realizations of the ITRF conventional reference frame are now commonly used: ITRF2005 (Altamimi et al. 2007a) and IGS05 (Ferland 2006a). The IGS05 was created by the IGS (Dow et al. 2005) to be compliant with the most recent standards in GNSS data processing. In Nov. 2006 both the IGS (Gendt 2006) and EPN switched from the use of relative antenna phase centre models to the absolute ones. To achieve the highest consistency, solutions obtained from a GNSS processing based on absolute models should be tied to an ITRS realization consistent with these absolute calibrations, such as the IGS05.

Independently of the method and the conventional frame used, the reliability of the alignment depends on the selected set of reference stations. Woppelmann et al. (2008) investigated the influence of using different reference station sets to express a global solution in a given frame and concluded that the best results were obtained using a large number of globally distributed reference stations, mitigating the individual reference station problems.

In this paper, we investigate the impact of the choice of (a) the reference frame realization (IGS05 or ITRF2005), (b) the reference stations and (c) the number of transformation parameters used in the minimal constraints on the GNSS positions computed in a network approach.

2. Input Data

The regional and the global GNSS networks used throughout this paper are based on IGS and EPN stations. The IGS network includes today about 400 continuously observing GNSS stations. A selection of 132 sites based on station performance, tracking record, monumentation, collocation and geographical distribution constitutes the IGS05 reference frame sites (Ferland 2006a) selected by the IGS Reference Frame Working Group for the IGS realization of the International Terrestrial Reference Frame (ITRF).

The regional network used throughout this paper consists of 42 well-distributed EPN stations (Figure 1); 23 of them are IGS05 reference sites. This regional network was complemented with 47 global IGS05 reference stations to form a global network covering homogeneously the Earth (Figure 2).

Almost one year of data from November 2006 to September 2007 (GPS weeks 1400 - 1445) has been processed with the Bernese software version 5.0 (Dach et al. 2007). The data analysis was based on GPS carrier-phase measurements, applying the ionosphere-free linear combination. When analysing double differences of the observations in a network approach, we solved for daily station coordinates, zenith tropospheric delay parameters using the wet-Niell mapping function (with the dry-Niell a priori model), horizontal tropospheric gradients and carrier-phase ambiguities (fixed to their integer values when possible). We used absolute antenna phase centre models and the IGS final orbits and Earth rotation parameters. The ocean tidal loading corrections were applied using the FES2004 ocean tide model (Lyard 2006).

Daily free network SINEX solutions were generated for both the regional and global networks. The regional and global daily solutions have been computed in such a way that the analysis-related coordinate differences are minimized: each day, the baselines used to process the regional network are saved and introduced as a priori to process the global network.

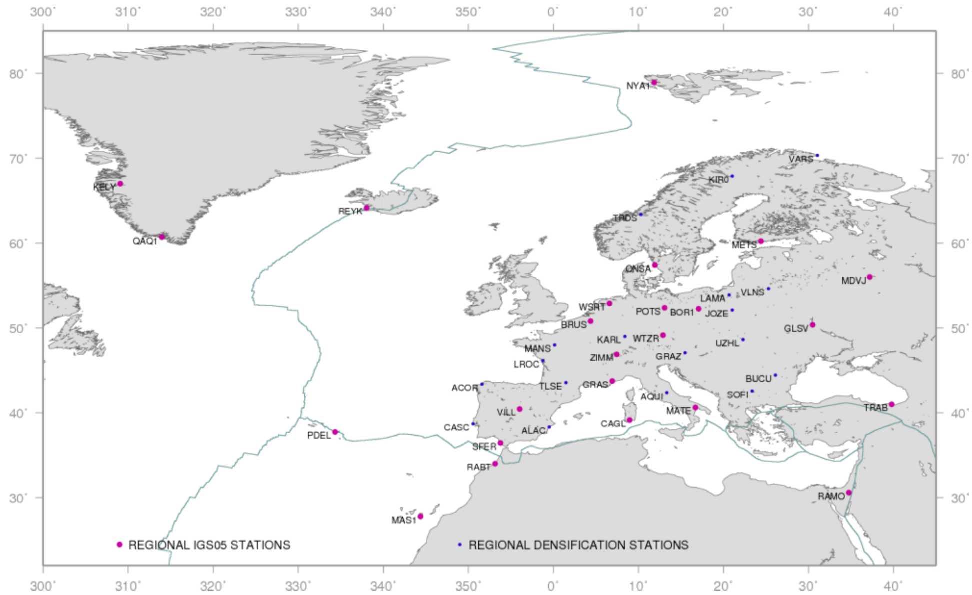

Figure 1: Regional Network

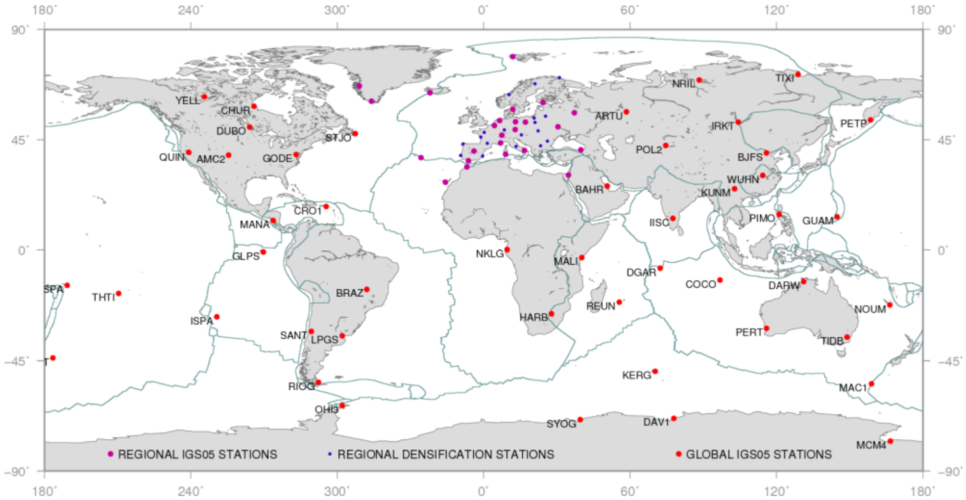

Figure 2: Global Network

3. Reference Frame Realization

3.1 Comparison of IGS05 and ITRF2005

Throughout this paper, two realizations of the ITRF2005 reference frame (IGS05 and the original ITRF2005) have been used. The IGS05 frame was created by adding station-dependent coordinate corrections to the ITRF2005. These corrections are mean coordinate differences obtained from 6 months (GPS weeks 1325-1364) of parallel solutions computed by several IGS analysis centres using relative and absolute antenna calibrations for a subset of the IGS stations (IGS05). The agreement between the results from the different IGS analysis centres ranges from the mm-level to about 1 cm (Ferland 2006b). The probable causes of the disagreement between analysis centres are the different processing strategies and the network effect. The “corrected ITRF2005” was then re-aligned with the original ITRF2005 through a 7-parameter transformation (Ferland 2006b) using more than 130 IGS reference stations. The resulting set of station velocities (same as ITRF2005) and coordinates is known as the IGS05.

Thanks to the 7-parameter transformation, the IGS05 and ITRF2005 are the same frame with a global average difference equal to zero. The RMS of the differences between ITRF2005 and IGS05 (Figure 3) is 7 mm with a maximum difference of 26 mm. They are mainly caused by the effect of the different antenna/radome models. However, when zooming on the European region (Figure 4), a systematic pattern between the IGS05 and ITRF2005 can be observed, resulting in a bias of about 4 mm in the up component.

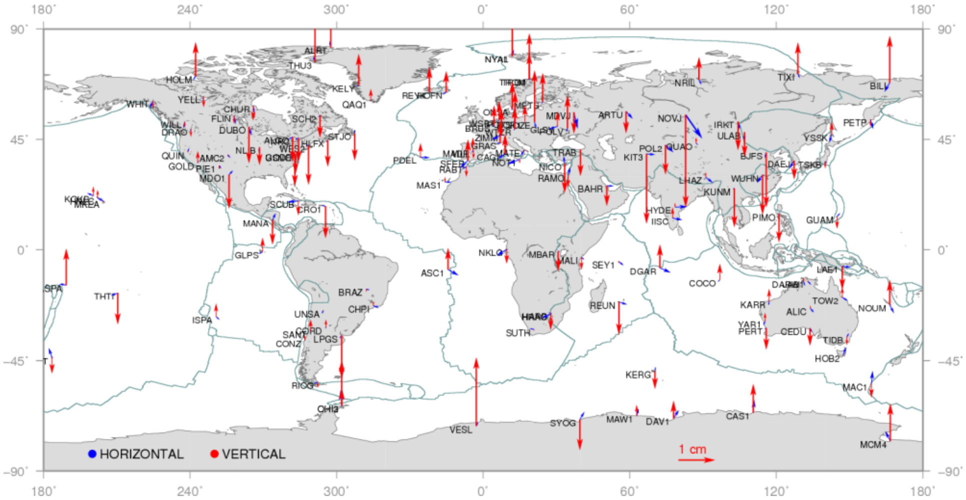

Figure 3: Position differences between IGS05 and ITRF2005 for all IGS05 stations

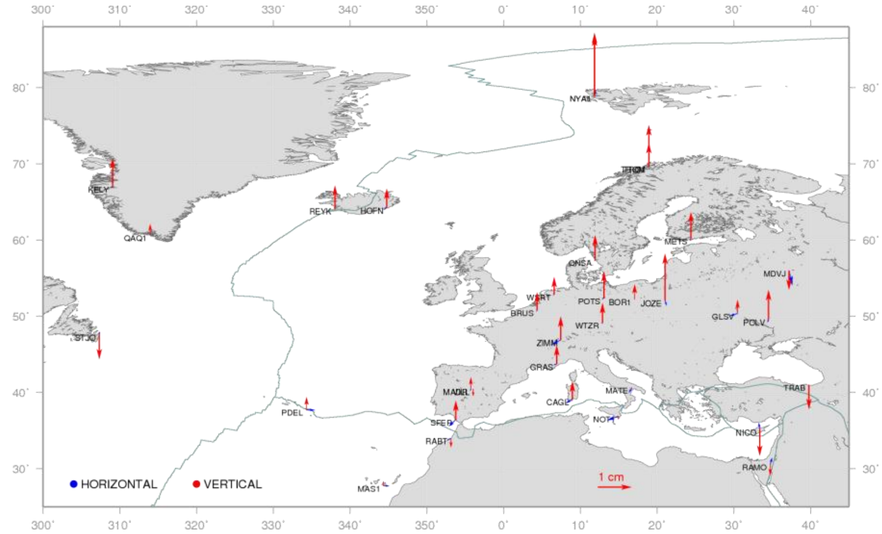

Figure 4: Position differences between IGS05 and ITRF2005 for all European IGS05 stations

The corrections used to create the IGS05 are only valid for the stations and their antenna/radome used during the parallel processing test period. While the IGS05 is designed for today’s GNSS processing using absolute antenna models, it consequently does not contain information for previous site solution numbers. These solution numbers indicate for each ITRF2005 station the validity time span of a specific coordinate and velocity. The absence of solution numbers for the period before May 2005 (beginning of the parallel solutions computed to construct the IGS05) makes the IGS05 unsuitable for reprocessing purposes. On the other hand, the ITRF2005 contains full historical information for 300 GNSS stations, but it is based on the relative antenna models and it has not been updated since Dec. 2005. Table 1 summarizes these differences and also shows that less IGS05 stations are available in Europe compared to ITRF2005 stations.

Table 1: A comparison between IGS05 and ITRF2005

	ITRF2005	IGS05
Antenna model	Relative	Absolute
Available solution numbers	Until Dec. 2005	From May 2005
# GNSS stations	300	130
# GNSS stations in Europe	79	30

3.2 Minimal constraints

The CATREF software package (Altamimi et al. 2007b) was used to stack the daily free network SINEX solutions to obtain a cumulative solution and to express it in a conventional reference frame (IGS05 or ITRF2005) under minimal constraints using a subset of reference stations.

The minimal constraint approach can be summarized as follows (Altamimi et al. 2007b):
The linearized form of the standard 7-parameter Helmert transformation between two reference frames X_R and X_S can be written as: $X_S = X_R + A\theta$ with

$$A = \begin{pmatrix} 1 & 0 & 0 & X_R & 0 & -Z_R & Y_R \\ 0 & 1 & 0 & Y_R & Z_R & 0 & -X_R \\ 0 & 0 & 1 & Z_R & -Y_R & X_R & 0 \end{pmatrix}$$ and $\theta = {}^{T}\left(T_X \quad T_Y \quad T_Z \quad D \quad R_X \quad R_Y \quad R_Z\right)$ with (T_X, T_Y, T_Z) the 3 translations, D the scale factor and (R_X, R_Y, R_Z) the 3 rotations.

The minimal constraint approach consists in expressing X_S and X_R in the same frame (i.e. $\theta = 0$). A least squares adjustment yields a solution for θ as follows: $\theta = \left(A^T A\right)^{-1} A^T \left(X_S - X_R\right)$ and consequently the minimal constraint condition can be imposed by adding the following constraint: $0 = B\left(X_S - X_R\right)$ with $B = \left(A^T A\right)^{-1} A^T$

The 7 columns of the design matrix A correspond to the 7 datum parameters. This matrix can be reduced to those parameters selected by the user.

As the computations cover only ten months, the velocities are not reliable and are removed from the solution. CATREF was used to obtain daily and weekly solutions, as well. However, in the following only the results from the cumulative solution will be shown. These results are representative for the daily and weekly solutions, which in fact show larger variations than the following results.

4. Results

4.1 ITRF2005 versus IGS05

The regional and the global solutions have been tied to IGS05 and to ITRF2005 by applying minimal constraints on translation, rotation and scale. To ensure the consistency with the ITRF2005 or the IGS05, the station discontinuities determined by the IGS were used, resulting, for each ITRF2005 station in a set of solution numbers identifying the validity time span of a specific coordinate.

The reference stations have been selected in such a way that:

- Stations showing coordinate differences of more than 7 mm in the horizontal components or more than 15 mm in up-component with respect to either the IGS05 or the ITRF2005 were rejected.
- Anytime a new solution number is introduced for a station after Dec. 2005, the station is removed from the list of potential reference stations.

Consequently, ten IGS05 stations have been rejected and we retained 62 reference stations for the global and 22 for the regional solution, both geographically well-distributed. The same set of reference stations have been used in the IGS05 and ITRF2005 cases.

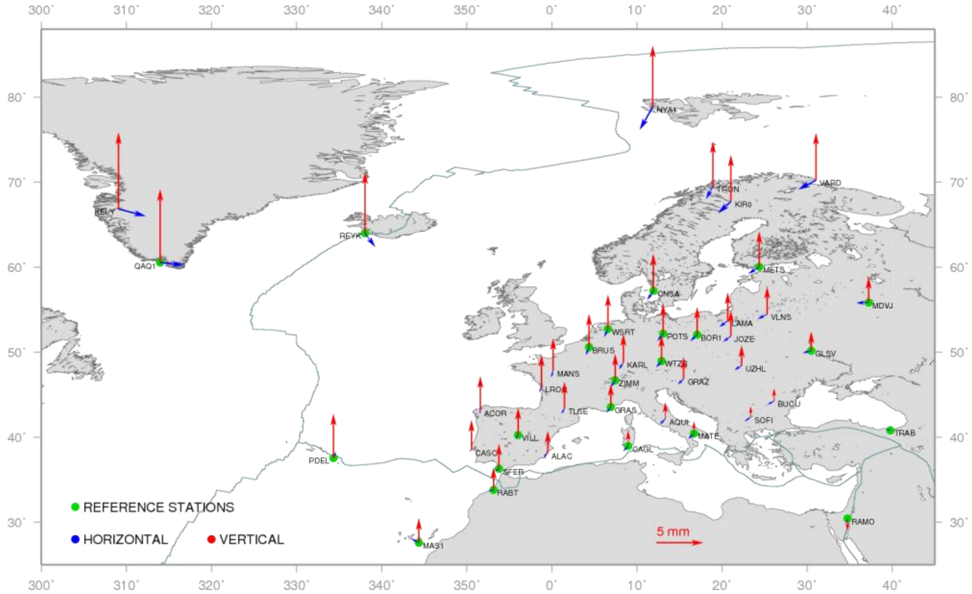

Figure 5: Position differences between the regional solutions expressed in IGS05 and in ITRF2005

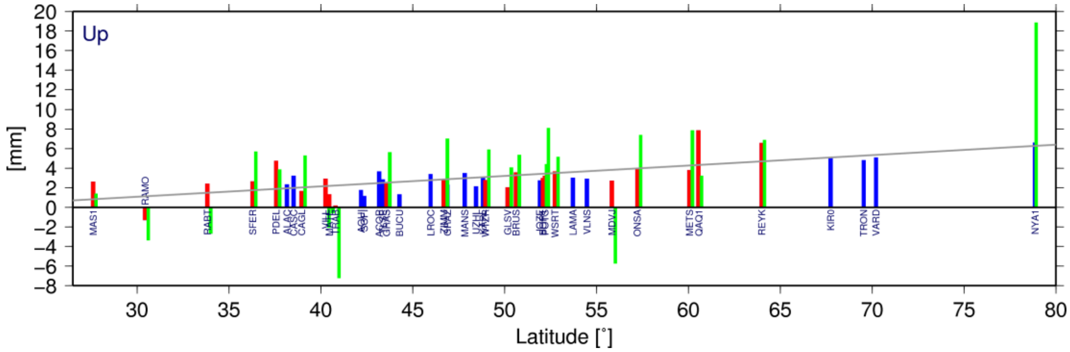

Figure 6: Comparison of the up component differences between the regional solutions tied to the IGS05 and to the ITRF2005 (reference stations in red, all the others stations in blue). The differences between the IGS05 and ITRF2005 official values are also indicated in green. Both are plotted as a function of latitude.

As expected, the comparison of our two global solutions, tied to the IGS05 and to the ITRF2005 shows only sub-mm coordinate differences. However, when comparing the two regional solutions (Figure 5), the station coordinate differences reach up to 8 mm in the vertical, with a bias of about 3 mm. Figure 6 highlights the correlation between the computed height differences and the coordinate differences between IGS05 and ITRF2005 in Europe; it demonstrates that the computed systematic height differences are caused by the regional tilt between the IGS05-ITRF2005 frames. Since the internal geometry of our network is preserved, the differences can be fully explained by a 7-parameter transformation.

4.2 Regional versus Global

When comparing the regional and global solutions, a first observation is that the differences can be fully explained by a 7-parameter Helmert transformation. This means that adding global stations to a regional network does not change the internal network geometry of the cumulative solution at the regional level.

First the stability of the global solution was assessed with respect to the chosen reference stations (Table 2): the impact of outliers in the reference stations and the impact of using different sets of reference stations (all fulfilling the same criteria). In both cases, the impact is below the 2-mm level for all stations and sub-mm for the European stations. Consequently, the stability of the global solutions allows considering the global approach as the ground truth.

Table 2: Stability of the global solution with respect to the chosen reference stations and coordinate outliers

Impact of	Solution 1	Solution 2	Position differences between the two solutions	
			Global	In Europe
Outliers in the reference stations	68 reference stations with 6 outliers (Up 25 mm / EN 15 mm)	62 reference stations without6 outliers	< 2 mm	< 0.8 mm
Different sets of reference stations	62 reference stations <7 mm in horizontal <15 mm in up	45 reference stations <7 mm in horizontal <15 mm in up	< 1.5 mm	< 0.5 mm

In order to test the impact of the selected reference stations used in the regional network, three sets of reference stations have been defined (Table 3):

- Selection A: all European IGS05 stations present in the solution (23), no criteria have been applied; the station NYA1 shows a difference of 2.2 cm in the up component with respect to ITRF2005;
- Selection B: 'Selection A' without NYA1; the agreement between the 22 remaining stations in the solution and ITRF2005 is now better than 4 mm in the horizontal components and 14 mm in the up component;
- Selection C: a set of 14 European IGS05 stations restricted to the continental part, which have residuals of the Helmert transformation below 5 mm in all three components with respect to the ITRF2005.
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Table 3: Residuals of the Helmert transformation between the 3 regional solutions and ITRF2005

	IGS05 reference stations								
	Selection A			Selection B			Selection C		
	East (mm)	North (mm)	Up (mm)	East (mm)	North (mm)	Up (mm)	East (mm)	North (mm)	Up (mm)
BOR1	0.7	-0.1	1.2	0.8	0.1	3.2	0.3	0.8	2.2
BRUS	-0.9	-0.1	1.0	-1.0	-0.1	2.6	-1.0	-0.2	-0.5
CAGL	-1.7	-0.1	-2.2	-1.5	-0.6	-3.5	0.1	0.8	-0.7
GLSV	-2.0	-3.0	-3.9	-1.6	-2.4	-1.8	-2.7	-1.2	0.2
GRAS	1.2	-0.1	-2.0	1.2	-0.3	-2.3	2.2	0.3	-1.9
MAS1	3.0	3.3	11.1	1.1	2.4	7.9			
MATE	-1.6	1.6	-3.6	-1.1	1.3	-4.5	-0.5	3.3	-0.4
MDVJ	2.9	-3.4	-5.5	2.9	-2.5	-1.8	1.7	-1.9	-2.0
METS	1.7	-0.4	1.6	1.4	-0.1	5.8	0.6	0.3	2.1
NYA1	0.4	2.1	21.8						
ONSA	0.4	-0.4	1.4	0.4	-0.3	4.6	-0.3	-0.1	0.4
PDEL	2.2	-7.2	2.0	0.6	-6.8	1.8			
POTS	0.2	-0.4	-3.7	0.3	-0.3	-1.7	-0.1	0.2	-3.6
QAQ1	-0.6	0.4	-12.0	0.0	1.8	-5.6			
RABT	2.6	2.5	-11.2	1.8	1.8	-13.5			
RAMO	-2.6	4.0	4.7	-0.3	3.8	2.4			
REYK	-1.2	1.8	-8.6	-0.8	2.0	-3.0			
SFER	-2.8	-0.4	4.0	-3.4	-1.0	2.2	-0.1	-1.6	1.2
TRAB	0.5	0.7	-8.2	1.9	1.5	-7.7			
VILL	-2.0	-0.3	2.0	-2.4	-0.6	1.2	-0.2	-1.2	-0.4
WSRT	0.8	-0.6	6.9	0.8	-0.6	9.0			
WTZR	1.3	0.7	1.6	1.4	0.7	2.8	1.3	1.4	2.3
ZIMM	-1.7	-1.9	1.4	-1.6	-2.0	1.9	-1.2	-1.6	1.2
min/max	-2.8/3.0	-7.2/4.0	-12.0/21.8	-3.4/2.9	-6.8/3.8	-13.5/9.0	-2.7/2.2	-1.9/3.3	-3.6/2.3

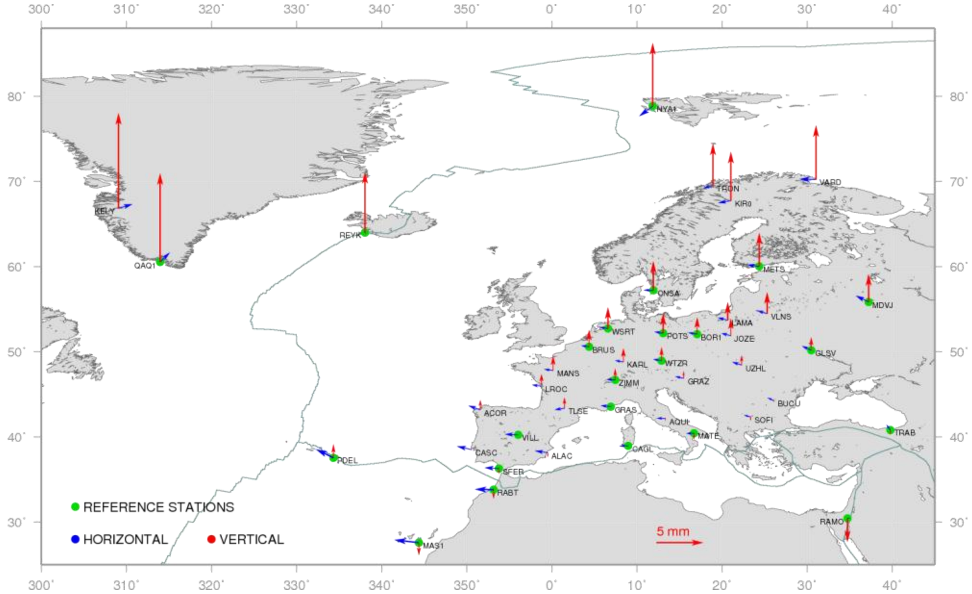

Figure 7: Selection A: position differences between the global and regional solutions in ITRF2005

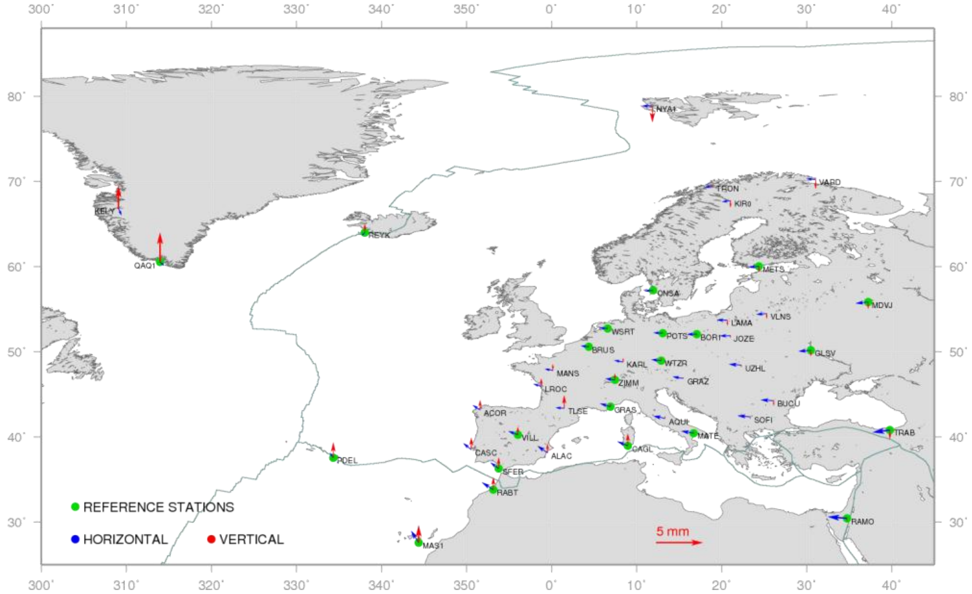

Figure 8: Selection B: position differences between the global and regional solutions in ITRF2005

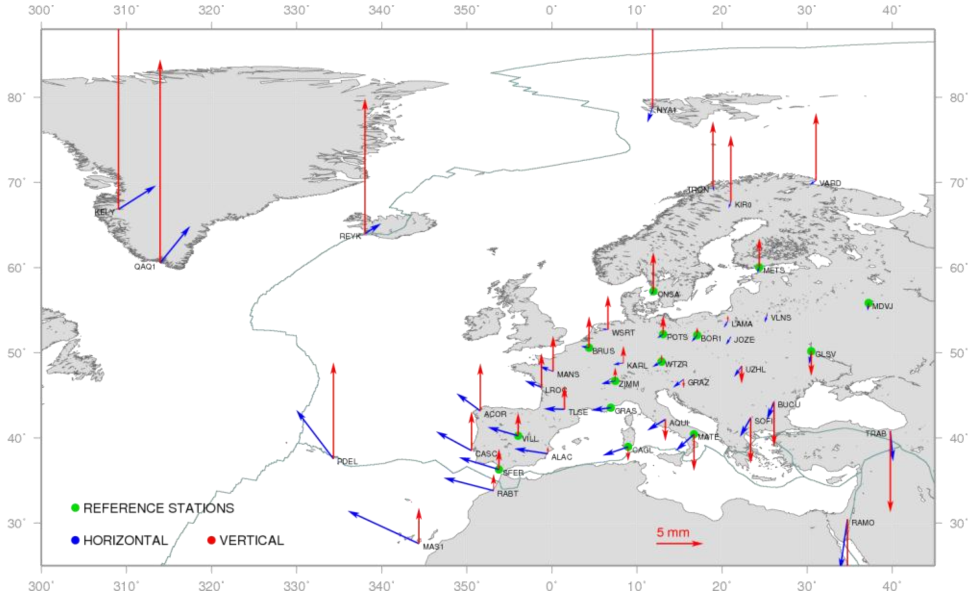

Figure 9: Selection C: position differences between the global and regional solutions in ITRF2005

The differences between the global and the different regional solutions tied to the ITRF2005 with each of the three sets of reference stations is shown in Figure 7 (selection A), Figure 8 (selection B) and Figure 9 (selection C).

For selection A, the position differences between the regional and the global solutions reach the cm-level in the up-component, while they are below 3 mm in the horizontal. When the station NYA1 is rejected from the list of the reference stations (selection B), the differences between the regional and the global solutions stay below 2 mm in the horizontal and 3 mm in the vertical. Finally, in selection C, where the reference stations are located only on the European continent, the differences between the regional and global solutions reach up to the 2-cm level in the vertical and 8 mm in the horizontal components. Border stations are mainly affected; nevertheless stations on continental Europe also can show discrepancies up to 5 mm both in the horizontal and vertical components. To complete the investigation, a similar test was done using the IGS05 reference frame. The global-regional position differences using selection B (Figure 10) reach up to 9 mm in the up component with a tilt and a bias of about 3 mm.

The big impact of NYA1 (Figures 7 and 8) is due to three factors: 1) the disagreement between the solution and ITRF2005, 2) its location far away from the barycenter of the network and 3) its lack of nearby stations allowing to mitigate the disagreement at NYA1. Consequently, this outlier is transposed into a tilt of the entire network (see Figure 7). A station with such a big outlier located on the European continent would have a completely different impact on the datum definition. Therefore, the reference stations need to be carefully verified before they are used for datum definition, especially if they are at the edge of the network. As in selection C, only a subset of reference stations in the center of the network is used, the residuals are amplified at stations close to the edge of the network. This shows that a proper distribution of the selected reference stations is an important issue in the geodetic datum definition. In conclusion, the border stations are essential for a proper datum definition and, at the same time, they suffer the most from a weak datum definition.

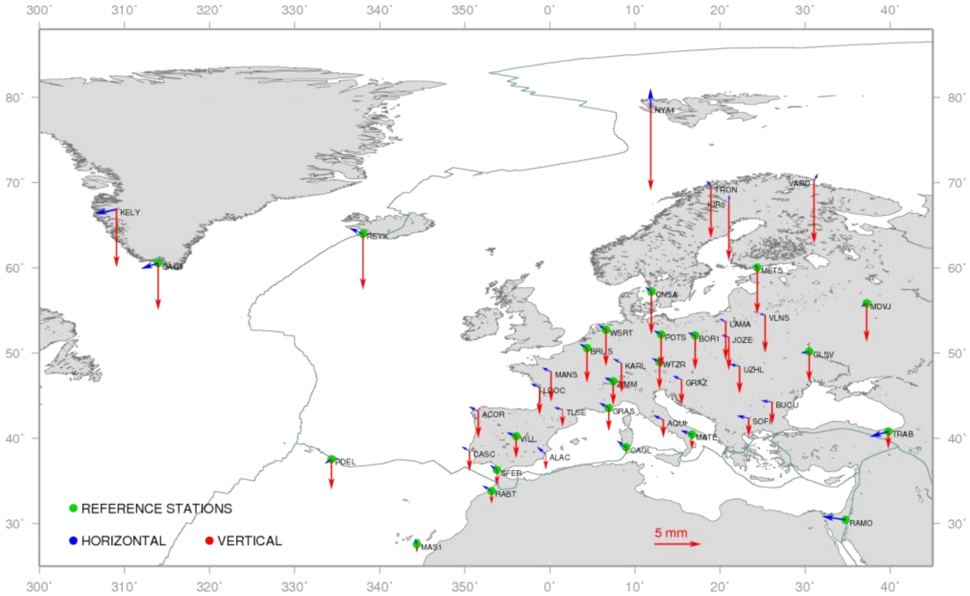

Figure 10:Selection B: position differences between the global and regional solutions in IGS05

4.3 Helmert Transformation Parameters

Table 4 gives the correlations of the seven Helmert parameters between the regional and global cumulative solutions and highlights the strong correlation of some translations and rotations, and of the scale with T_X and T_Z.

Table 4: Correlations of the seven Helmert parameters between the regional and global cumulative solutions

	T_X	T_Y	T_Z	D	R_X	R_Y
T_Y	0.0					
T_Z	-0.3	-0.1				
D	-0.5	-0.1	-0.6			
R_X	0.0	0.8	-0.1	0.0		
R_Y	-0.8	0.0	0.7	0.0	0.0	
R_Z	0.1	-0.7	0.0	0.0	-0.3	0.0

These correlations depend on the geometry of the network used to estimate the Helmert parameters. Similar correlations are observed when tying the regional network to the reference datum using 7-parameter minimal constraints. This is confirmed by the following tests: the minimum constraints method was applied with different types of constraints, as TRS (3 translations + 3 rotations + scale), TR (3 translations + 3 rotations), and T (3 translations, as recommended by Dach et al. 2007). We observe that:

- TRS has the potential to provide the most consistent results between the regional and global solutions. However, as it is extremely dependent on the choice of the reference stations, it is difficult to know which set of reference stations will guarantee this consistency. Depending on the choice of the reference stations, the most significant differences (up to the cm-level) between regional and global are seen in the vertical component (a tilt and bias).
- In the case of T, the regional solution is more stable and varies less depending on the chosen reference stations. In general, T entails larger differences (up to 6 mm using IGS05 and 5 mm using ITRF2005) in the horizontal components, but significantly reduces the vertical bias and tilt which can often be seen when TRS is used.
- In the case of TR, compared to TRS we observe no improvement in the vertical and larger differences in the horizontal. In addition, TR is again dependent on the reference stations used.

- Next to being dependent on the choice of T, TR, and TRS, the behaviour of the coordinates also depends on the choice of the underlying reference frame (IGS05 or ITRF2005) which was already indicated in section 4.1. For example, when comparing two regional solutions (selection B) tied to the IGS05 and ITRF2005, we see a tilt and bias in the vertical component when using TRS or TR. However, when using T, the tilt disappears and only a bias is left between IGS05 and ITRF2005. In all cases, the bias is about 3 mm.

In conclusion, as can be seen from the correlations (Table 4), there are too many degrees of freedom when using the seven parameters with a regional network. But, in the case of T, there are not enough parameters to ensure a proper alignment of our regional network as shown by the increased effect on the horizontal. TR is also an imperfect approach because of the correlations between translations and rotations and its inability to handle the effect on the horizontal also observed in the case of T.

All these investigations show that none of these above geocentric standard approaches is optimal for tying a regional network to a global frame. The usage of minimal constraints in a dedicated regional approach, where the rotations and scale refer to the barycenter of the network instead of the origin of the global coordinate system, should be a more satisfactory approach.

5. Conclusions

Using minimal constraints, different approaches to define the geodetic datum of a GNSS network, computed originally as a free network, have been investigated. We distinguished regional and global solutions and used both the IGS05 and ITRF2005.

Sub-mm differences are observed between our two global solutions, where one is tied to the IGS05 and the other to the ITRF2005. However, considering only a regional (European) network, we observe coordinate differences between the solutions tied to IGS05 and ITRF2005, respectively. These differences are caused by the regional disagreement between the ITRF2005 and IGS05 over Europe and reach up to 8 mm in the vertical with a tilt and a bias of about 3 mm.

At the regional level, the choice between the IGS05 or ITRF2005, the selection of the reference station set and the number of parameters used to apply the minimal constraints is crucial. As shown, different regional solutions can show biases (up to the cm-level) with respect to each other. Therefore, authors which do not explicitly describe how their solutions are tied to the reference frame (reference frame, reference stations, transformation parameters), provide incomplete information.

Due to the correlation of the Helmert parameters in a regional network, none of the standard geocentric minimal constraints originally developed for global networks (whatever the number of transformation parameters) are suitable for regional networks. It would be worthwhile to investigate if the usage of a dedicated regional minimal constraints method where the rotations and scale refer to the barycenter of the network instead of the origin of the global coordinate system provides more satisfactory results.

Anyway, at this stage of the investigations, the recommended approach is to use a global network as it behaves more stable and is less sensitive to the reference stations and frame.

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