# EUREF Activities at the CODE Analysis Center

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## Abstract

Besides being one of currently seven IGS analysis centers, CODE also plays a significant role in the maintenance and densification of the European Reference Frame (EUREF). The main task of EUREF is the establishment, maintenance and enhancement of a 3-dimensional European Reference Frame. Within the framework of EUREF, CODE participates as one of currently ten Associate Analysis Centers (AACs) and is responsible for the combination of the individual AAC results into an official EUREF combined solution. Each of the EUREF AACs processes a certain subset of the available European permanent GPS receivers. Results based on a complete (GPS-) week worth of data are submitted by each of the AACs in the Software INdependent EXchange (SINEX) format. Consequently all AAC SINEX files are rigorously combined on a weekly basis into the official EUREF (weekly) combined solution. At CODE the European network is also used to test and study different processing strategies. In this paper results of the different processing strategies are presented. Furthermore some information and results of the weekly EUREF combinations and the combination of all weekly EUREF solutions into a unique set of station positions and velocities are given. This combined solution, spanning 65 weeks and including all permanent EUREF GPS stations, has been submitted to the IERS to be included into the new ITRF solution.

## Introduction

The Center for Orbit Determination in Europe (CODE) is a joint venture of the following institutions:

- the Federal Office of Topography (L+T), Wabern, Switzerland
- the Institut Géographique National (IGN), Paris, France
- the Institute for Applied Geodesy (IfAG), Frankfurt, Germany
- the Astronomical Institute of the University of Berne (AIUB), Bern, Switzerland

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The CODE is located at the AIUB and uses a cluster of six DEC Alpha processors for the GPS data processing. All the GPS analyses at CODE are performed with the Bernese GPS Software Version 4.1 [*Rothacher and Mervart*, 1996].

The CODE Analysis Center, as implied by its name and the participating institutions, lays special emphasis on Europe in two respects:

- the European region is over-represented in the global CODE solutions produced for the International GPS Service for Geodynamics (IGS). This should guarantee that the CODE orbits are of as good a quality as possible over Europe,
- a special solution for some 35 European sites is routinely computed to monitor the European sites not present in the global solution and the European reference frame.

In the following discussion we will focus on this European solution. More information about CODE may be found in [*Rothacher et al.*, 1996*a*].

# The European Solution at CODE

The special European solution is generated on a daily basis with a delay of 11 days. This processing delay was chosen to allow for data from remote sites to arrive at the IGS and/or EUREF data centers in time. The original goals of the European solution were to:

- verify the quality of the CODE orbits for large regional networks,
- monitor all permanent European sites,
- maintain and enhance the European reference frame by combining the results of the European solution with our global solution,
- test different/new processing strategies,
- find the optimal processing strategy for regional networks which is important in view of the IGS densification project [*Zumberge and Liu*, 1994].

However, since the start of the weekly EUREF combination in the beginning of 1996 [*Brockmann and Gurtner*, 1996], the need to monitor all permanent European sites at CODE has disappeared, because the processing of all permanent European GPS stations is now distributed among several (currently 10) EUREF AACs. Also it is no longer necessary to combine our European solution with our global solution since this task was taken over by the EUREF combination together with the global combination done by the IGS Global Network Associated Analysis Centers (GNAACs). The GNAACs combine all global IGS solutions (currently 7) with several regional solutions like EUREF.

CODE uses the European solution to verify the quality of its final IGS orbits. This orbit monitoring, using stations which were not included in the global CODE solution, has been performed since the start of the IGS in 1992. At that time the number of baselines was very limited (2–4). The effect of an orbit error $dR$ on baseline length $L$ is given by the following "rule of thumb", see [*Baueršíma*, 1983; *Zielinski*, 1988]:

$$dL = 0.25 \cdot dR \cdot \frac{L}{R} \qquad (1)$$

where $L$, $dL$ are baseline length and baseline length error and $R$, $dR$ are satellite distance and orbit error.

With our regional European network having a diameter of approximately 6000 km, and our orbit quality which is believed to be of the order of 50 mm, the effect ($dL$) on the baseline length would thus be of the order of 3 mm, only! Consequently, with the current orbital precision, it will be hard to see an orbit induced effect in this network!

## Processing Strategies

At CODE initially five different European solutions using slightly different estimation strategies were generated for each day. These solutions can be characterized as follows:

EGB: Baseline-wise processing without ambiguity fixing using a cut-off angle of $20^o$. The tropospheric delays are modelled by estimating one zenith delay parameter for each hour (24-parameters per day and station). The normal equations of the individual baselines are combined, including the combination of the troposphere parameters, to create a full network solution. Because for large networks it is very CPU-intensive to correctly correlate all double difference observations, this solution is used to study the effect of neglecting these correlations.

EG_: Full network solution without ambiguity fixing using a cut-off angle of $20^o$. As opposed to the previous solution (EGB) the correlations are treated correctly.

EQ_: Same as EG_-solution but with ambiguities fixed to their integer values. On the average 90% to 95% of the ambiguities are resolved. The ambiguity fixing is performed using the so-called Quasi-Ionosphere-Free (QIF) ambiguity resolution strategy [*Mervart*, 1995]. This solution is performed to study the impact of ambiguity fixing. The weekly EUREF contribution from CODE was based on this solution type up to GPS week 0899.

ET_: Same as EQ_-solution but here the tropospheric delay estimates from the CODE global solution are used for those stations which are common to both networks (global and European). The idea behind introducing tropospheric delays based on a global GPS solution is, that in regional networks it is difficult or even impossible (depending on the size of the network) to correctly estimate the *absolute* tropospheric delays. Therefore it could be advantageous to introduce troposphere estimates for at least one of the regional sites.

EQB: Same as EQ_-solution but using a cut-off angle of $15^o$. Here we study the effect of lowering the cut-off angle. A lower elevation cut-off angle should give a better decorrelation of the station height and tropospheric delay estimates. However, lower elevation data will probably be nosier and show more cycle slips and multipath effects. The weekly EUREF contribution from CODE is based on this solution since week 0899.

Table 1 shows the internal consistency of these five different solutions based on the first 80 days of 1997. The results were generated by combining the daily normal equations of the 80 consecutive days estimating one set of station coordinates (no velocities). The coordinate rms errors were computed using the daily station residuals, in the local north, east and height directions, with respect to the combined 80-day solution after applying a 7-parameter Helmert transformation. Note that all five solutions were generated in exactly the same way except for the difference in estimation strategy outlined above!

Table 1: Repeatability of the European solutions at CODE based on the first 80 days of 1997. Repeatability is given in millimeters.

| Sol. ID. | Correct Correl. | Amb. Fix. | Ele. Cut. | Repeatability N | E | U | Remarks |
|---|---|---|---|---|---|---|---|
| EGB | NO | NO | 20 | 2.4 | 3.3 | 8.5 | Baseline corr. |
| EG_ | YES | NO | 20 | 2.1 | 2.9 | 7.3 | Amb. free |
| EQ_ | YES | YES | 20 | 1.9 | 1.7 | 7.2 | Amb. fix |
| ET_ | YES | YES | 20 | 1.9 | 1.7 | 6.7 | Global Tropo. |
| EQB | YES | YES | 15 | 1.9 | 1.7 | 5.7 | cut-off $15^o$ |

Based on the results shown in Table 1 the following conclusions are drawn:

- Correct correlation of the double-difference observations is very important for the height components (a result of the correct weighting of the troposphere parameters).

- Fixing the ambiguities to their integer values gives a significant improvement for the east component of the coordinate estimates. The improvements for the north and height components are insignificant.

- Introducing the tropospheric delay estimates from the CODE global solution improves the height component of the coordinate estimates. This is remarkable considering the diameter of the network (6000 km) which should allow for an accurate recovery of the absolute tropospheric delays! We expect that for small networks the height improvement will even be (much) larger.

- Changing the cut-off angle from $20^o$ to $15^o$ gives a very significant improvement for the height component. Apparently the lower elevation data is of good quality. Therefore the solution can profit fully from the decorrelation of the tropospheric delay estimates and the height estimates, thanks to the improved geometry of the observations.

## New Processing Strategies

Based on the experiences gained with our European solutions it is clear that we should start trying to use a lower elevation cut-off angle in GPS data processing. However, at this point, we only know that a cut-off angle of $15^o$ gives better repeatabilities than a cut-off angle of $20^o$. This does not tell us what the optimal cut-off elevation is; it might be as low as $0^o$ or somewhere between $15^o$ and $20^o$. Furthermore, if we start to use lower elevation data, the mapping function used to map the tropospheric zenith delay estimates to different elevations will become more important too. Down to $15^o$ the mapping function does not play a significant role. However, at lower elevations, the mapping function starts to become important. Therefore different mapping functions should be studied and tested. Weighting of the data should be considered as well because lower elevation data will tend to be noisier. Also systematic effects, like for instance multipath, will most likely show up more strongly and more frequently. Therefore weighting schemes should be studied. Of course data weighting cannot remove systematic errors in the observations but it can reduce the influence they have on the estimated parameters.

Based on these considerations we added three new solutions to our European processing. These new solutions can be characterized as follows:

NMF: Same as EQB-solution but using the Niell Mapping Function [*Niell*, 1993]

NMW: Same as NMF-solution but using an elevation-dependent weighting. The weight of the undifferenced observations is given by the cosine squared of the zenith angle .

NM5: Same as NMW-solution but using a elevation cut-off angle of $5^o$.

Table 2 shows the internal consistency of these three new solutions and four of the "old" solutions based on days 089–109 of 1997. The results were generated as described in the previous section.

Table 2: Repeatability of the European solutions at CODE based on days 089–109 of 1997. Repeatability is given in millimeters.

| Sol. ID. | Amb. Fix. | Ele. Cut. | Map. Func. | Ele. Wgt. | Repeatability N | E | U | Remarks |
|---|---|---|---|---|---|---|---|---|
| EG_ | NO | 15 | SAAS | NO | 1.9 | 2.7 | 4.9 | Amb. Free |
| EQ_ | YES | 20 | SAAS | NO | 1.5 | 1.4 | 5.9 | Amb. Fix |
| ET_ | YES | 20 | SAAS | NO | 1.5 | 1.4 | 5.5 | Global Trop |
| EQB | YES | 15 | SAAS | NO | 1.6 | 1.4 | 4.8 | cut-off $15^o$ |
| NMF | YES | 15 | NMF | NO | 1.6 | 1.4 | 4.9 | Niell Map. |
| NMW | YES | 15 | NMF | YES | 1.4 | 1.3 | 4.9 | Ele. Weight |
| NM5 | YES | 5 | NMF | YES | 1.4 | 1.3 | 4.4 | cut-off $5^o$ |

## Discussion of Processing Strategies

Table 2 clearly shows that lowering the cut-off angle significantly improves the height component. An interesting effect is visible in the solutions with elevation-dependent weighting. By applying the elevation-dependent weighting one hopes to reduce effects of the noisy low elevation data on the horizontal components, which can quite clearly be observed. At the same time one would expect the height component to "suffer" from the weighting which, however, is not the case. Both, the weighted and unweighted solutions using the same cut-off angle ($15^o$), show the same consistency of the height component.

With the weighting scheme systematic effects due to multipath effects should also be reduced. This was tested by comparing the resulting coordinate solutions based on the 21 days. The weighted solutions at $15^o$ and $5^o$ cut-off were closer to the $20^o$ solution than either of the unweighted $15^o$ solutions. This indicates that the weighting indeed reduces the systematic effects present in the lower elevation data. In fact the mean height difference between the unweighted $15^o$ and $20^o$ solutions, after a seven parameter Helmert transformation, is larger than the repeatability of those solutions! This is a clear indication that the systematic effects are much larger than the consistency of the individual solutions. At this time it is impossible to tell which of the two solutions is closer to the "truth". The coordinates of the weighted $15^o$ and even the $5^o$ solutions are closer the the $20^o$ solutions than the coordinates of the unweighted $15^o$ solutions. However, the coordinate difference between the $5^o$ solution and the $20^o$ solution is larger than the difference between the weighted $15^o$ solution and the $20^o$ solution. Also the a posteriori rms of the data processing is slightly higher for the lower elevation processing. This indicates that the weighting scheme needs some improvement. Different weighting schemes will therefore be studied and tested in the near future.

# The EUREF Combination at CODE

Since mid 1996 weekly SINEX contributions from different European AACs are combined into an official weekly EUREF solution. This EUREF combined solution is then submitted to the IGS for inclusion into the IGS densification pilot project performed by the GNAACs [*Zumberge and Liu*, 1994]. Within EUREF the decision has been made to submit one official European (EUREF) solution to the IGS and to combine the different European solution on the EUREF level.

The number of permanent GPS receivers is growing very rapidly all around the world and also in Europe. This makes it very difficult to process all permanent station at one single Analysis Center. Especially the task of verifying the site specific information, like antenna heights and antenna types, becomes difficult. This is why within EUREF it was decided to set up a distributed processing scheme in which an unlimited number of AACs can participate. Each AAC can focus on its own region of interest and submit its local solution to be combined with the other local European solutions. In this way an almost unlimited number of stations can be processed. At the same time the expertise, needed

Table 3: The different EUREF Analysis Centers and their contributions to the EUREF weekly combinations.

| AAC | Description | #sta | Weeks |
|---|---|---|---|
| ASI | Nuova Telespazio S.p.A., Space Geodesy Center, Italy | 7 | 0867-0898 (29) |
| BEK | International Commission for Global Geodesy of the Bavarian Academy of Sciences (BEK), Germany | 14 | 0834-0898 (65) |
| COE | European solution created at CODE, Switzerland (Center for Orbit Determination in Europe) | 37 | 0834-0898 (65) |
| GOP | Geodetic Observatory Pecny, Czech Republic | 11 | 0890-0898 (9) |
| IFG | Institute for Applied Geodesy (IfAG), Germany | 16 | 0834-0898 (65) |
| LPT | Bundesamt für Landestopographie, Switzerland | 6 | 0880-0898 (19) |
| NKG | Nordic Geodetic Commision (NKG), Norway | 27 | 0878-0898 (20) |
| OLG | Observatory Lustbuehel Graz (OLG), Austria | 17 | 0853-0898 (45) |
| ROB | Royal Observatory of Belgium (ROB), Belgium | 12 | 0836-0898 (63) |
| WUT | Warsaw University of Technology (WUT), Poland | 16 | 0834-0898 (60) |
| EUR | Euref Combined solution created at CODE | 56 | 0834-0898 (65) |

to process GPS data for high precision geodesy, is distributed among several different agencies. The growth of the number of EUREF AACs underlines the success of the concept of distributed processing. At the start in mid 1996 there were 5 EUREF AACs. In early 1997 the $10^{th}$ EUREF AAC became operational. The number of processed stations is growing very rapidly as more AACs join EUREF and more permanent stations become available.

Within the IGS the GNAACs combine the official EUREF and other regional solutions with the global solutions of the seven IGS Analysis Centers. The resulting "polyhedron" will then be used for future ITRF realizations. In fact, the polyhedron combinations *are* weekly realizations of the ITRF, based solely on GPS.

The EUREF AACs are listed in Table 3 but more details about the individual EUREF analysis centers and EUREF in general can be found in the IGS annual report for 1996 and at the EUREF Central Bureau at the Royal Observatory in Brussels, Belgium, which is accessible through the World Wide Web using:

- http://www.oma.be/KSB-ORB/eurefhome.html
- ftp://ftpserver.oma.be/pub/astro/euref

## Combination Scheme

The combination of regional solutions is performed using a sequential least-squares adjustment. The combination is statistically correct (equivalent to a least-squares adjustment using all original GPS observations together in one step) assuming that there are no correlations between the observations of each of the sequential solutions. This assumption is true, if we combine, e.g., daily network solutions into weekly, monthly, or annual solutions. If there are correlations between the observations of different sequential solutions, this independence is not given. The "anchor site" concept (sites common to different solutions) tries to account for these neglected correlations but the procedure is not absolutely correct from a statistical point of view either. The observations of these anchor sites are introduced into the combined solution at least twice.

The estimation of the variance-covariance components is essential for the combination of results from different processing centers. Thanks to the fact that most European Analysis Centers (all except ASI) process the data using the Bernese GPS Software (version 3.5 or 4.0) and very similar processing options, the variance-covariance factors for each solution can be derived directly from the data sampling rate. Only for ASI the factor had to be estimated. Because in 1996 all centers agreed to use 180 second data the scaling could be set to 1 for all centers except ASI which still uses a 30 second data sampling. However, to give the resulting EUREF solution a realistic covariance matrix – the GPS formal errors are normally much too optimistic – the scaling factors were increased.

The results of all the EUREF AACs are received in the SINEX format. As a first step in the combination the SINEX-files are converted into normal equation files (NEQ-files). These NEQ-files can be put directly into the Bernese GPS Software program ADDNEQ [*Brockmann*, 1996; *Rothacher and Mervart*, 1996] which is used to generate the EUREF weekly combinations. Note that all individual AACs using the Bernese GPS Software, also use the ADDNEQ program to combine the NEQ-files of their daily solutions into a weekly (SINEX) solutions.

The program ADDNEQ first removes all constraints from the individual solutions and then applies the covariance rescaling. Two different combinations are made subsequently. One using a free network solution and one using fiducial sites. In both solutions the same stations are used to define the reference frame. In the free network solution the geodetic datum is defined by specifying 6 reference frame constraints (no-net translation and no-net rotation conditions) for the selected reference sites. The free solution is performed since it helps to identify problems in the combination. The fiducial solution gives the official EUREF weekly solution.

After the successful combination of the week considered, the combined solutions of the last 7 weeks are combined with the new week to see whether the new weekly solution agrees with the previous ones. A jump in the coordinates of individual sites is easily detected in this step. Finally, the combined solution is made available at the anonymous ftp servers at AIUB (Euref Combination Center, Switzerland), CDDIS (IGS global data center), IfAG (IGS regional data center), and ROB (EUREF Central Bureau, Belgium).

# EUREF Contribution to IERS/ITRF

In early 1996 the International Earth Rotation Service (IERS) decided to produce a new realization of the International Terrestrial Reference Frame (ITRF). It was thought that thanks to the IGS densification project the EUREF stations would also show up in the new ITRF. It turned out, however, that at the moment, due to the "pilot" status of the IGS densification project, there is no guarantee that all the permanent EUREF stations should show up in the new ITRF realization. Therefore it was decided that a separate EUREF contribution would be made and submitted to the IERS to be included into the new ITRF realization.

Table 3 shows which EUREF AACs contributed to the EUREF contribution to the IERS. A description of all the AACs, the number of stations they processed, and the number of weekly solutions is given. When starting to generate the EUREF IERS contribution a lot of problems were detected in the early EUREF weekly combinations. Especially problems with antenna heights and antenna types. It was therefore deemed necessary to reproduce all the EUREF weekly combinations. Furthermore, several problems were detected when looking at the time series of the coordinates. Care had to be taken to remove erratic coordinate solutions from the weekly combinations. These site problems had very different causes and some are unexplained untill now. Most problems were seen in all the individual EUREF AAC contributions which indicates that something was wrong with the site rather then with the analysis. Only on very few occasions there was a problem with one of the individual EUREF contributions. Some of the detected site problems are:

WETT and MADR: Problems with the "old" rogue receiver

MATE: "Flange" put around the antenna (40 mm height jump)

KIRU: Snow on antenna (30 mm height effects)

MEDI: Work on nearby VLBI antenna causing noisy east component

Within the IGS it was decided to change the reference frame for all the IGS products from ITRF93 to ITRF94 reference frame starting with GPS-week 860. In GPS solutions without orbit estimation the reference frame is given by the orbits. Because all the EUREF solutions are computed using the IGS (or CODE) orbits without further orbit adjustment, the reference frame change of the IGS orbits can be seen in the EUREF weekly coordinate solutions as a clear jump. Therefore we have to account for the reference frame change from ITRF93 to ITRF94 in the combination. Because no reliable transformation parameters between the ITRF93 and ITRF94 are available they were estimated by combining an equal number of EUREF solutions (without velocity estimation) before and after the reference frame change and then comparing the resulting two coordinate sets. The determined transformation parameters between the two sets were then applied to all EUREF results prior to week 860 during the actual combination. The estimated transformation parameters were 3 translations and 3 rotations. Note that the relatively large rotation drift differences between the ITRF93 and ITRF94 were neglected! In view of the relatively short timespan

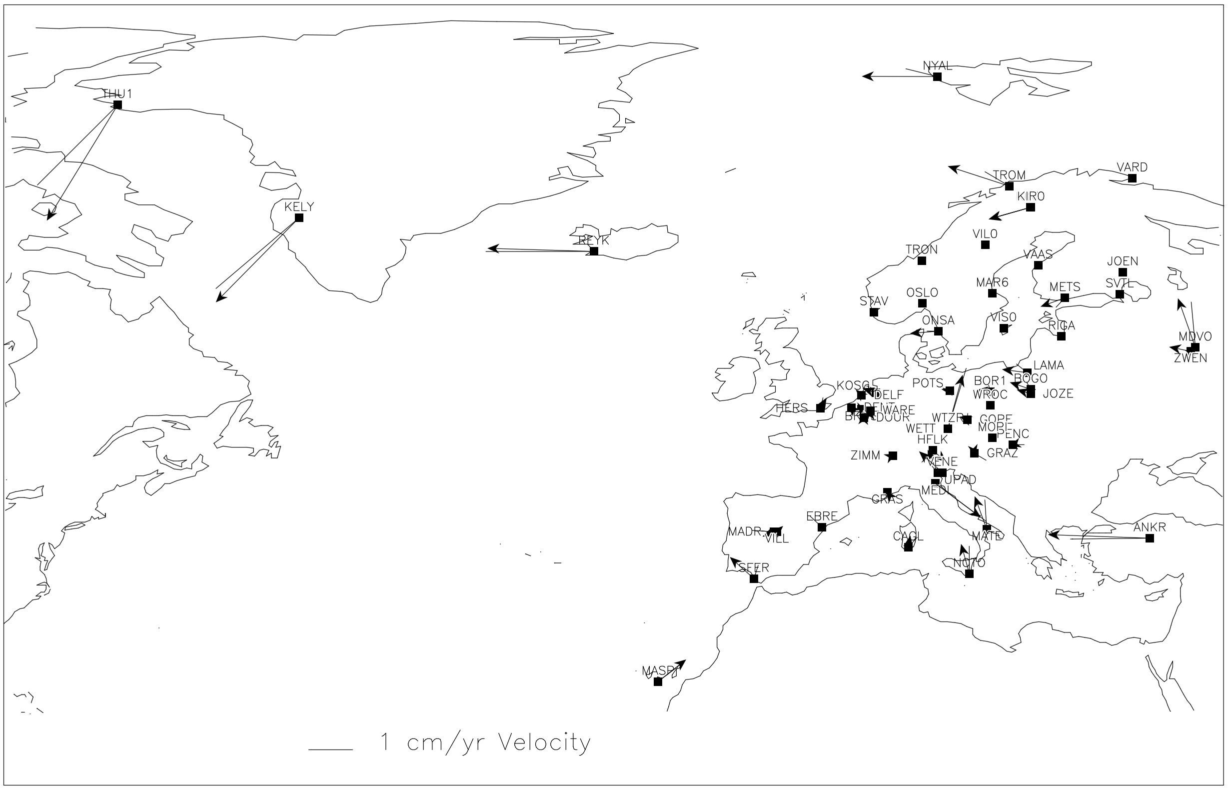


Figure 1: Velocities derived from EUREF (arrows) and CODE (lines) European weekly solutions based on GPS-weeks 834–898. Velocity of WTZR was set to zero

covered by the EUREF weekly solutions this should not cause any problems. By accounting for the reference frame change in this way the combination could be based on a continuous series (no reference frame "jumps") in the ITRF94. Finally, we also had to account for the changes in the horizontal antenna phase center offsets for the Trimble antennas. These changes were caused by the introduction of a new set of constant *and* elevation-dependent antenna phase center offsets in week 860, within the IGS [*Rothacher and Schaer*, 1996; *Rothacher et al.*, 1996*b*]

In the actual combination the velocity of the site "WTZR" was constrained to its ITRF94 value and only horizontal velocities were estimated. For sites with an observation history of less than 30 weeks no velocities were estimated at all, they were constrained to the Nuvel-1 velocities. No other constraints were applied. The results of this 65 week combination were submitted to the IERS in the SINEX format. The results and may also be found on the anonymous ftp account at CODE (directory EUREF/IERS).

To verify the obtained velocity results two so-called "zero-velocity" fields were computed: one based on the weekly EUREF combinations and the other on the weekly EUREF contributions from CODE. For the determination of these zero-velocity fields the velocity of the site "WTZR" was set to zero. Figure 1 shows these two zero-velocity fields. For both solutions the same timespan was used and the weekly results were combined in exactly the same way. All sites which are on the stable Eurasian plate (like WTZR) should show the same (zero) velocity vector. Therefore all non-zero velocity vectors are are either stemming from sites which are not on the stable Eurasian plate or the estimated velocity vectors are in error. Clearly the velocity estimated for the site "WETT" is in error! It should be equal to the velocity of the site "WTZR" since these are essentially at the same location. The error is caused by the receiver problems at "WETT", mentioned earlier in the text. Obviously some problems remain in the EUREF combinations. The sites THU1, KELY, and REYK are located on the North-American plate and therefore show a large velocity vector. Some sites in the Mediterranean area show significant velocity vectors which was to be expected since this is a tectonicly active region. Finally, there seems to be a small problem with the northern sites in the EUREF solution, especially NYAL, TROM, and KIRU seem to be affected. This might be some residual effect from the reference frame change (drifts), or stem from an inconsistency in the individual solutions that were combined. Within the EUREF combination there are some small unresolved problems with the solution of the NKG which processes a large Scandinavian network. Maybe this has led to some problems with the northern sites. However, one has to keep in mind that a timespan of only 65 weeks was available which is not very long for velocity estimation.

As a final check the coordinates of the EUREF combination were compared to the CODE contribution to IERS based on the global CODE solution and a European solution which was based on the weekly CODE contributions to EUREF covering the same timespan as the weekly official EUREF solutions. The results of this comparison are given in Table 4. The coordinate sets were compared using a seven parameter Helmert transformation, the given rms values are based on the residuals of all stations after the transformation. The rms over all residuals for the north, east and height directions (local coordinate system) and the total three-dimensional rms are given. Clearly all three solutions can be considered to be of the same high quality. The consistencies of the three coordinate sets also shows that there are no visible orbit biases present. The quality of the regional series is as good as the quality of (the European network in) the global solution from CODE.

Table 4: Coordinate comparisons between one global and two regional solutions (using Helmert transformations).

| Solution 1 | Solution 2 | RMS N, E, U, Total | | | |
|---|---|---|---|---|---|
| EUREF | CODE Global | 1.7 | 1.8 | 4.7 | 3.2 |
| EUREF | CODE Europe | 1.5 | 1.4 | 3.7 | 2.5 |
| CODE Europe | CODE Global | 1.8 | 1.4 | 3.0 | 2.2 |

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