Processing Strategies for Regional GPS Networks

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ABSTRACT

At the Center for Orbit Determination in Europe (CODE), one of the IGS Analysis Centers, we are routinely processing the GPS data of a dense European network. In order to improve the height estimates and, very strongly coupled therewith, the modelling of the troposphere for this network, we decided to include *low-elevation data* into the processing, something that has been done in VLBI analyses for a long time. An appropriate mapping function, the option to weight the observations according to the elevation angle, and the estimation of troposphere gradients were implemented to make best use of the data at low elevations. Problems may arise from phase center variations, multipath, and the troposphere.

143 days have been processed so far using the new processing options and data down to 5 degrees elevation. Comparing the results to a standard 15-degree elevation cut-off solution shows, that the use of low-elevation data together with an elevation-dependent weighting of the observations reduces the scatter in the height estimates by about 20–30 percent. The estimation of tropospheric gradient parameters improves the repeatability in the horizontal site coordinates by a factor of two for sites successfully tracking down to 10 degrees and below.

INTRODUCTION

The *Center for Orbit Determination in Europe (CODE)*, one of seven IGS Analysis Centers (IGS = International GPS Service for Geodynamics), is a collaboration of four European institutions and is located at the University of Berne in Switzerland [*Rothacher et al.*, 1997]. The main task of the CODE Analysis Center consists of the daily generation of global products within the framework of the IGS. In addition, CODE is routinely producing regional GPS solutions for a dense network of European stations, mainly due to the following reasons:

- The European solutions from CODE are combined with other regional European solutions computed by other centers (see [*Bruyninx*, 1997; *Springer et al.*, 1997]) to improve and maintain *EUREF*, the *EUropean REference Frame*.
- Because the European solutions are based on the global products from CODE (GPS orbits, Earth rotation parameters, etc.), these solutions provide a good check for the quality of the daily CODE products.

Paper presented at the IAG General Assembly, 1997, Rio, Brazil, September 3–9, 1997

- The network is ideal to perform tests with new processing strategies for regional networks.

The *standard* European solution routinely produced at CODE — in addition there are always a few test solutions running — is a full network solutions including the sites shown in Figure 1.

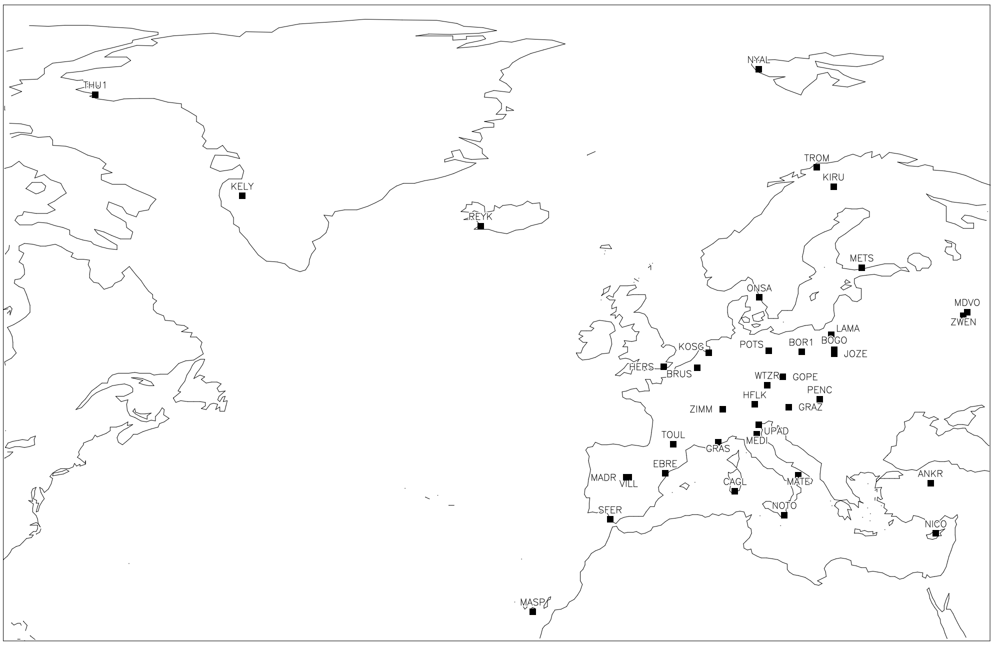

Figure 1: Network of 41 European IGS sites processed on a daily basis by the CODE analysis center.

The correlations between all double-difference observations (sampled at 180 seconds) are correctly modeled [*Beutler et al.*, 1986, 1987]. Tropospheric zenith delay parameters are estimated once per hour for each site using the Saastamoinen mapping function. The elevation cut-off angle is set to 15 degrees. About 85 percent of the ambiguities in the network are resolved to integers using the QIF strategy [*Mervart et al.*, 1994].

NEW SOLUTION STRATEGIES

New processing strategies were developed with the idea, that low-elevation data (from the conventional 15-degree elevation cut-off down to 5 degrees) should be included in the processing. The inclusion of low-elevation data has two major advantages:

- The number of observations increases by about 25 percent when going from 20 degrees to 5 degrees and about 13 percent from 15 to 5 degrees. These numbers are valid for actual data from the European IGS network. When looking at simulated data (full tracking down to 5 degrees) the increase would be almost 40 percent and 28 percent, respectively.
- A better decorrelation between the estimated height and the troposphere delay parameters of the same station: the correlation coefficient changes from -0.96 to about

-0.83 when going from 20 degrees down to 5 degrees elevation cut-off [*Rothacher and Beutler*, 1997].

To make sure that the use of low-elevation data is not going to deteriorate the solution quality, we decided to add three new features to the software (which will be described in more detail below), namely: implementation of an appropriate mapping function, elevation-dependent weighting of the observations, and the option to estimate troposphere gradients.

Niell Mapping Function

The mapping functions developed by [*Niell*, 1993] (one for the dry and one for the wet part of the tropospheric delay) were implemented into our software [*Rothacher and Mervart*, 1996]. The Niell mapping functions were derived from radiosonde data and proved their usefulness for processing VLBI data. To produce the results presented below, only the dry mapping function was used to map the *total* delay.

Elevation-Dependent Weighting

Tropospheric refraction and multipath are responsible for a considerable increase in the scatter of the observations at low elevations. After a few tests with different models for an elevation-dependent weighting of the phase observations, we adopted a weighting function $w(z)$ where the noise increases in the same way with elevation as the tropospheric delay, namely:

$$w(z) = \cos^2(z), \tag{1}$$

where z is the zenith distance of the satellite. Thus an observation at zenith is assumed to have unit weight.

Tropospheric Gradients

When using lower elevation angles, the azimuthal variations of the tropospheric delay will play an increasingly important role. A relatively simple model proposed by [*Davis et al.*, 1993; *MacMillan*, 1995] and generalized here for any mapping function is given by:

$$\Delta r(\alpha, z) = m_f(z) \cdot \Delta r_h + \frac{dm_f(z)}{dz} \cdot \cos\alpha \cdot \Delta r_n + \frac{dm_f(z)}{dz} \cdot \sin\alpha \cdot \Delta r_e \tag{2}$$

where

z,α	...	zenith distance and azimuth angle of the satellite
$\Delta r(\alpha, z)$	...	troposphere delay in the direction (α, z)
Δr_h	...	zenith delay parameter
Δr_n	...	gradient parameter in north–south direction
Δr_e	...	gradient parameter in east–west direction
$m_f(z)$	...	mapping function

Δr_h is the conventional zenith delay and Δr_n and Δr_e are the two gradient parameters of the model. The model corresponds to a tilting of the mapping function by an angle β in the direction α with

$$\beta \approx \frac{\sqrt{{\Delta r_n}^2 + {\Delta r_e}^2}}{\Delta r_h}. \tag{3}$$

New Solution Types

On March 30, 1997 (day 089), four new solution types were implemented into the routine processing of the European network based on the three software modifications discussed above. These solution types are listed in Table 1 together with the standard solution A.

Table 1: Standard solution A and four new solution types.

Solution Type	**Mapping Function**	**Elev.-Dep. Weighting**	**Elevation Cut-Off**	**Gradient Estimation**
A	Saastamoinen	No	15^o	No
B	Niell (dry)	No	15^o	No
C	Niell (dry)	Yes	15^o	No
D	Niell (dry)	Yes	5^o	No
E	Niell (dry)	Yes	5^o	Yes

For an easy interpretation of the results, each solution type only differs by one option from the previous one, i.e., the new features are activated one by one. When estimating gradients one set of parameters was set up per day (i.e., one north and east component per station and day).

The results presented in the next section are based on the 143 daily solutions that have been accumulated since the start of the new solution series. Each one-day solution in general contained 30–35 European sites.

RESULTS

To get an idea of the differences between the solution types A to E we discuss two important aspects below: the *systematic effects*, by looking at the parameters of *Helmert transformations* between the solutions, and the *repeatability* of the coordinates over the series of 143 days as a measure of the *quality* of the solutions (there is no ground truth with sufficient accuracy available).

Systematic Effects

Table 2 shows the rms errors and parameters of the Helmert transformations between coordinate solutions generated by combining all 143 daily solutions for each strategy.

Table 2: 7-parameter Helmert transformations between pairs of European solutions generated from 143 days of data using different processing options (see Table 1).

Transformation	**RMS of Transf. (mm)**			**Rotations (mas)**			**Scale**
between	**North**	**East**	**Up**	**x-axis**	**y-axis**	**z-axis**	**(ppb)**
A and B	0.3	0.3	1.3	0.0	-0.3	0.0	1.9
B and C	0.6	0.5	3.5	0.0	0.0	0.0	1.2
C and D	0.8	0.7	2.6	-0.1	-0.1	0.0	-0.5
D and E	1.0	0.6	1.4	-0.1	0.3	0.0	0.4
A and E	1.5	0.9	2.8	-0.2	-0.1	0.0	2.9

We clearly see that changing the mapping function from Saastamoinen to Niell results in a noticeable scale change of 1.9 ± 0.1 ppb. Weighting the observations also produces a scaling of the network in the same sense (1.2 ppb). All processing changes (A to E) sum up to give a scale change of almost 3 ppb with respect to solution A. The rotations of the network are relatively small.

The rms of the transformation in North, East, and Up directions indicate that the major changes in the height coordinates occur when weighting the observations and by going to low-elevation data, whereas the major change in the horizontal coordinates takes place when estimating troposphere gradients. This will be confirmed in the next section.

Coordinate Repeatabilities

The site Onsala serves as an example here because its receiver performs very well and tracks the satellites down to a few degrees. Due to its location at the shore we may expect quite significant and rapid changes in the behaviour of the troposphere. Figure 2 shows the repeatability in all three components of the site Onsala over the 143 days processed. Let us summarize the most important findings:

- The change of the mapping function did not change the *repeatability* rms error (in contrast to the systematic effects seen in the previous section).
- The biggest improvement in height results from the elevation-dependent weighting of the observations and the inclusion of low-elevation data.
- A small improvement in the horizontal position is obtained by weighting the observations, whereas the data at low elevations degrades the horizontal position.
- The estimation of troposphere gradients has definitely the largest impact on the results by improving the horizontal positions by a factor of two (from 2 to 1 mm) compared to the standard solution A. The small degradation of the height component visible for solution E is due to the reduction of the number of troposphere zenith delays from 24 to 8 per session for this solution (reducing computer resources).

Many pronounced peaks in the North and East coordinate series disappear when estimating gradients. We think it quite improbable that the gradient parameters solely absorb multipath effects and antenna phase center variations. In view of the fact that a permanent site with a good performance collects almost the same amount of data from the same satellite constellation every day (apart from a change in time by 4 minutes a day), phase center and multipath biases in the estimated coordinates should be varying rather slowly with time (periods of weeks to one year).

Figure 3 demonstrates, that improvements similar to those for Onsala may be achieved for most of the sites *tracking down to 10 degrees elevation or below.*

Comparing the standard solution A to the best-performing solution E, we see a clear improvement in the repeatability of both, the vertical and the horizontal components. One has to emphasize in this context that the availability of low-elevation data of good quality is crucial to obtain the type of results shown above. Several sites in Europe are not (yet) delivering data below 15 degrees or are not performing as well (old receiver types, bad environment) and no improvement can be seen for such sites.

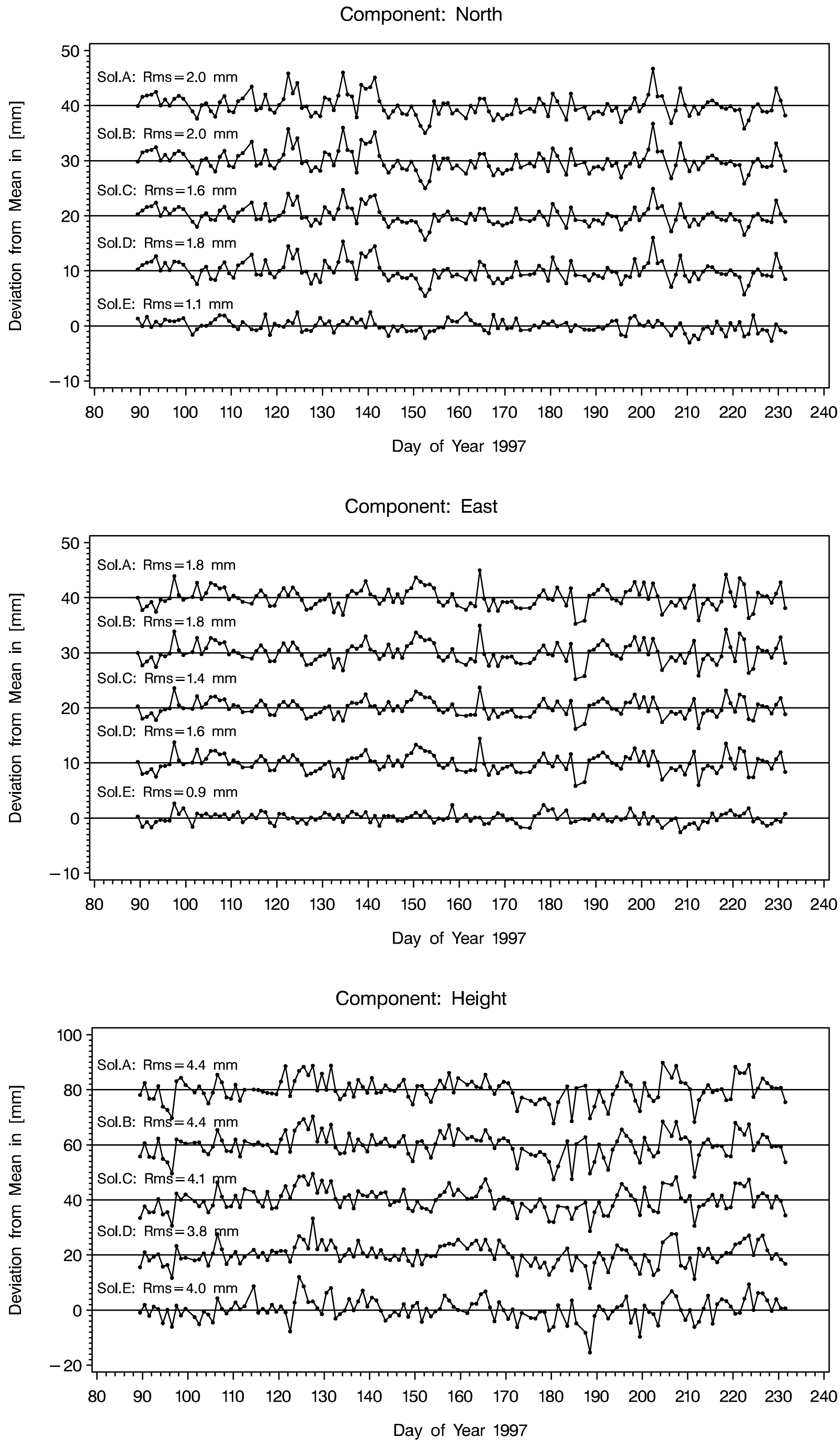

Figure 2: Repeatability of the site coordinates (North, East, and Height) of Onsala for 143 daily solutions using different processing options (see Table 1). The rms error with respect to the mean is given for each solution type.

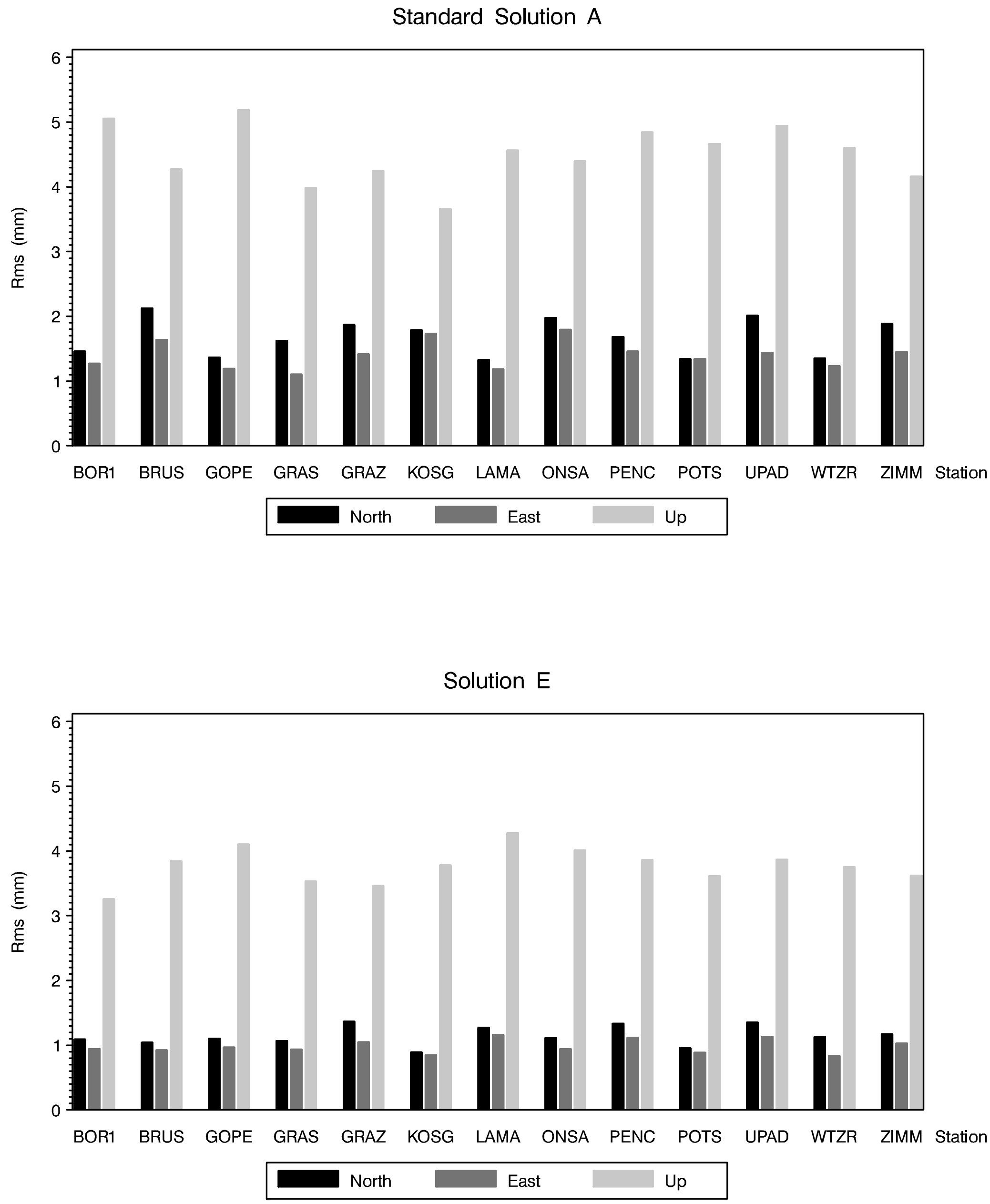

Figure 3: Repeatability of station coordinates in Europe for the standard solution A and the best-performing solution E (see Table 1) over a period of 143 days.

CONCLUSIONS

Several new processing options (inclusion of low-elevation data, a better mapping function, elevation-dependent weighting of the observations, and the estimation of troposphere gradients) to improve the troposphere modelling and thus the station heights were tested using the European IGS network.

From the results we conclude that by including low-elevation data the extremely high correlation between station heights and troposphere zenith delay parameters is considerably reduced. Using elevation-dependent weighting of observations we account for the increased scatter of the data at low elevations and reduce undesirable effects of multipath. The result is a decrease of the daily height rms by about 20–30 percent. Let us mention, that low-elevation data and elevation-dependent weighting of observations are beneficial in many other GPS-related domains like estimation of satellite clocks with code and phase measurements, ionospheric modelling, ambiguity resolution, etc.

The estimation of tropospheric gradients improves the horizontal position estimates by almost a factor of two, provided that enough low-elevation data is available and an elevation-dependent weighting is applied. We therefore highly recommend that GPS data should be collected down to *as low an elevation angle as possible* for all applications aiming at highest precision. When selecting a location for a GPS site, this should be taken into consideration, too. It should be emphasized, that *successful ambiguity resolution* is a pre-requisite to obtain improvements as shown above. Whether the gradients estimated from GPS data may indeed be interpreted as azimuthal variations in the troposphere, remains to be seen, e.g., by comparing the GPS results with meteorological measurements and models.

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