Combination of GPS Solutions for Densification of the European Network: Concepts and Results Derived from 5 European Associated Analysis Centers of the IGS

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1. Introduction

Since the beginning of the activities of the IGS (International GPS Service for Geodynamics) (BEUTLER et al. 1994c) in 1992 the number of permanently operating GPS receivers increased steadily. At the CODE *(Center for Orbit Determination in Europe)* Analysis Center of the IGS e.g. 25 global sites were analyzed in 1992, whereas more than 75 sites are processed in 1996 to derive products such as satellite orbits and Earth rotation parameters. The situation in Europe is similar: Currently (June 1996) we have more than 30 permanent GPS sites operating continuously (see Figure 1). In addition to that we should address also the numerous nationwide GPS networks (e.g. the Swedish SWEPOS network (HEDLING and JONSSON 1995) has already a history of about 3 years).

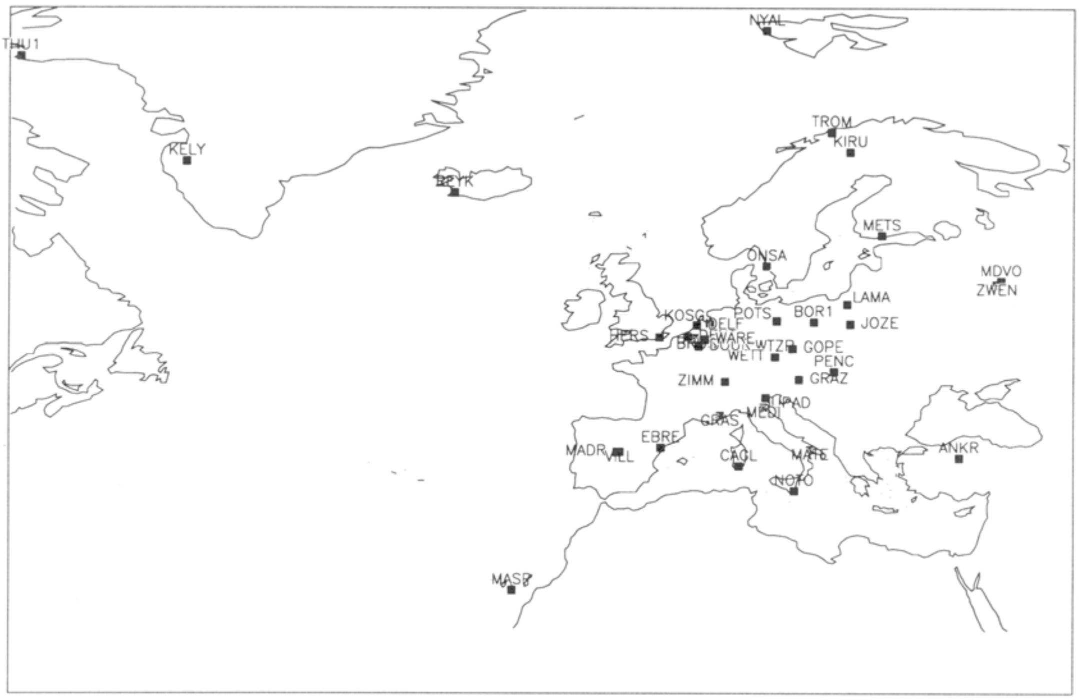

Figure 1: The European permanent GPS sites (38) processed by 5 Local Associated Analysis Centers (LNAACs).

From the point of view of *orbit determination* it makes no sense to include a large number of local sites in the global solutions of the IGS Analysis Centers. From the point of view of the *reference frame realization* we obtain coordinates of the local sites in a best (consistent) way by processing the local sites simultaneously with the global sites.

The Distributed Processing Concept enables a consistent reference frame realization without the necessity of a simultaneous processing of local sites together with global . sites. *Local Network Associated Analyses Centers* (LNAAC) have the possibility to process the local sites of their interest together with 3-4 global IGS sites. These additionally processed sites are necessary to enable the

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link to the global network. They are therefore called *anchor sites.* The result of the LNAACs is a so-called *SINEX (Software INdependent EXchange)* file which contains the coordinate results together with the variance covariance and other information. This infbrrnation may then be used to combine local solutions with regional or global solutions.

Since the beginning of the year 1996 5 European LNAACs are producing under the umbrella of EUREF coordinate results on a weekly basis (in analogy to the weekly SINEX submissions of the IGS Analysis Centers). At present a real distributed processing in Europe is not yet realized. Lots of sites are processed by several LNAACs. This fact is on the other hand very well suited to perform comparisons showing the agreement and the consistency between the different contributions. Consistency values are shown in Section 3. The computation of weekly combined EUREF solutions is the main result of the presented studies. We intend to make them available to the IGS from July 1996 onwards.

2. Concepts of Distributed Processing

2.1 SINEX Format

A milestone for the distributed processing was the 1994 IGS workshop *Densification of the IERS Terrestrial Reference Frame through Regional GPS networks (JPL,* Pasadena, Dec. 1994). There it was decided to start a pilot project to proof the concepts of a *distributed processing.*

A test format of a Software INdependent EXchange format called SINEX (Version 0.05) (KOUBA 1995a), was defined by a working group. Since GPS week 817 (Sept. 3, 1994) most of the IGS Analysis Centers produce weekly coordinate solutions in the mentioned format.

The SINEX format contains - besides the coordinate estimates and the corresponding covariance information - other important information like site names, DOMES numbers, antenna types, antenna eccentricities, phase center values, receiver types, and information on apriori weights (apriori values and apriori covariance matrix). Now a final SINEX version 1.0 is ready (KOUBA 1996) which is the official exchange format within the IGS for all contributions later than July 1996.

As mentioned already in the introduction: This software independent exchange format (SINEX) is the basis for the distributed processing. If the different GPS software tools are able to support this format, results of the Associated Analysis Centers may be performed independently of the used software. The advantage of software independence is also used for the combination of solutions for the definition of the ITRF *(International Terrestrial Reference Frame)* (BOUCHER 1994 and 1996). All contributions of the different space techniques (VLBI, SLR, GPS, DORIS) have to be given in the mentioned format, too.

Here we focus on combination solutions stemming from GPS, only.

2.2 Processing Regional or Local Networks

We mentioned already that Regional or Local Networks can be included into global network solutions only, if *anchor sites,* which are processed by the IGS Analysis Centers, are also included in the processing. Furthermore it is important that the processing options are as consistent as possible with the global solutions. That includes the used orbit information, the Earth rotation parameters, the troposphere handling, etc. The impact of inconsistent processing strategies, as well as inconsistent combination strategies is given by (BROCKMANN 1996). We would like to point out, that the consistency of the solutions is the most important topic for the distributed processing because distributed processing has to approximate the simultaneous processing of all sites.

From the statistical point of view this distributed processing is indeed only an approximation, because the observations of the anchor sites are introduced into the combined solutions twice (or even more if the anchor sites are used by several LNAACs).

2.3 Combination Method

The combination of the local solutions, as well as the combination of regional with global solutions, bases on *the sequential least-squares adjustment* (WOLF 1978). That means that the results (site coordinates) and the asso- ciated variance-covariance information are used to pro- duce a combined solution using the principles of superposition of normal equations. The combination is statistically correct (equivalent to a common least-squares adjustment using all original GPS observations in one step), if 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 to week ly, monthly, or annual solutions.

If there are correlations between the observations of diffe- rent sequential solutions, this independence is not given. The anchor site concept tries to compensate these neglected correlations. But, as mentioned already, this concept is also not absolutely correct from statistical point of view.

2.4 Scaling of the Covariance Matrices

The estimation of the variance-covariance components is essential for a combination of results of different processing centers. The formulas of the variance-covariance component estimation (KOCH 1988) are not considered in this paper. Due to the fact that all European Analysis Centers process the data using *Bernese software 3.5 or 4.* 0 (ROTH- ACHER 1993), we may achieve variance-covariance factors for each solution directly from the used sampling rate. That ensures that all solutions get about **the** same weights in the combination. Table I gives the corresponding factors for the scaling of the normal equations.

Tab. 1: Scaling factors for normal equations used for the combination of th edifferent weekly solutions. The Analysis Center codes arew given in Section 3.1

	Local Analysis Centers				
	BEK	COD-E	IFG	ROB	WUT
Sampling in sec	180	180	180	120	30
NEQ Rescalind	1.00	1.00	1.00	0.66	0.16

2.5. Combination scheme

The combination of the solutions is shown in Figure 2. SINEX files (. *SNX),* or . ANEQ files (ASCII normal equation file of *Bernese 3.5)* are the input of the combination. The combination is performed using the *Bernese* program ADDNEQ which needs binary . NEQ files as in- put. The conversion programs SNXNEQ (for. SNX files) and NEQFMT (for. ANEQ files**)** convert the input files to the appropriate input format. As a result we obtain a combined SINEX file as well as a summary file **(.** *Sum).*

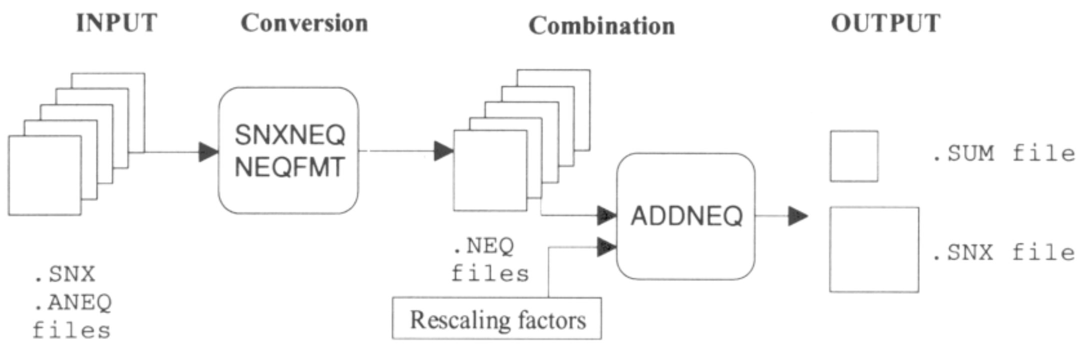

Fig. 2: Combination scheme at CODE: Computation of a combined weekly EUREF solution using the contributions of several LNAACs.

3. Results Using the Data of 5 Regional Analysis Centers

3.1 Analyzed Data

Since the beginning of the year 1996 we have 5 Local Network Associated Analysis Centers (LNAACs) contributing to the distributed processing in Europe. We analyzed about 3 months (GPS weeks 834-847) of weekly results of the following LNAACs:

- *International Commission for Global Geodesy of the Bavarian Academy of Sciences (BEK):* 12 sites
- *Center for Orbit Determination in Europe (CODE):* "Europe-only-solution'(COD-E) using 33 sites
- *Institute for Applied Geodesy in Germany (IfAG): 13* sites
- *Royal Observatory ofbeigium (ROB):* 11 sites
- *Warsaw University of Technology (WUT):* 10 sites

3.2 Combined Solutions

We performed two types of different solutions:

- Type A: Combination of the results of single Analysis Centers
- Type B: Combination of the results of different Analysis Centers for the same time interval

Solution type A gives information concerning the *internal precision (repeatability)* for each LNAAC. An introduc- tion of resealing factors is not necessary if we assume that all solutions of a particular LNAAC are produced using the same sampling rate for all weeks.

Solution type B gives information concerning the *consistency* between the Analysis Centers. For this solution type the use of the resealing factors of Table 1 is important.

We should mention that we performedfree *network solu- tions* (BROCKMANN 1996b). The geodetic datum is selected by no-net-transiation conditions with respect to ITRF93 (using the WETT, BRUS, ZIMM, MADR, MATE, and KOSG). No site coordinates are tightly constramed. The information concemnig the rotational defmition of the network is used from the network results. We solved for no additional Helmert parameters in the combination process. For the comparisons between the different individual solutions we used a 7-parameter Helmert transformation. That was done because we would like to analyse the internal precision of the network results and not the information concerning the definition of the geodetic datum. We show no values of this a posteriori estimated Heimert parameters in this paper.

3.3 Repeatability Values

Table 2 shows the results achieved from solution type A. For comparison we the repeatability values of daily solutions (COD-E1; from which we compute the weekly solutions) are also included. The repeatability of the weekly solutions is better by a factor of about 2. That is slightly less than we would expect from the law of error propagation

(v'7 = 2.6).

Tab. 2: Analyzed data, number of sites, and repeatability for each Analysis Center. The repeatability for the components North (N), East (E), and Up (U) is derived from Helmert transformations comparing each free weekly network solution (using all sites) with the free combined solution of the entire interval.

Analysis Center	number of weeks	number of sites	component	Helmert rms in mm
COD-E1 1-day	12	33	N E U	3.0 4.8 12.7
COD-E 7-day	12	33	N E U	2.4 2.2 7.3
BEK	9	12	N E U	2.1 2.4 9.1
IFG	12	33	N E U	2.1 2.6 5.8
ROB	12	33	N E U	1.0 0.9 2.9
WUT	12	33	N E U	1.5 2.1 2.9
Combined EUR Solution	12	33	N E U	2.5 2.3 8.2

The different weekly repeatability values are dependent on the the size of the network. The Center ROB, with the smallest values, processes the smallest network (longest baseline below 900 km). The European solution COD-E covers a much larger area (sites with the largest distance of 5800 km). We therefore cannot derive a quality value for each Analysis Center ftom these repeatability values. Nevertheless we will use this results as a reference for the comparison of the different solutions of the same week (solution type B).

3.4 Combined European Solutions

A combined solution (type B) was created for each week according to the combination scheme described in Section 2.5. Figure 3 shows the differences between the combined solution and the contributing solutions for the height components for one particular site. The site KOSG is used, because 4 of the 5 Analysis Centers process this station. There exists no site, which is processed by all Analysis Centers.

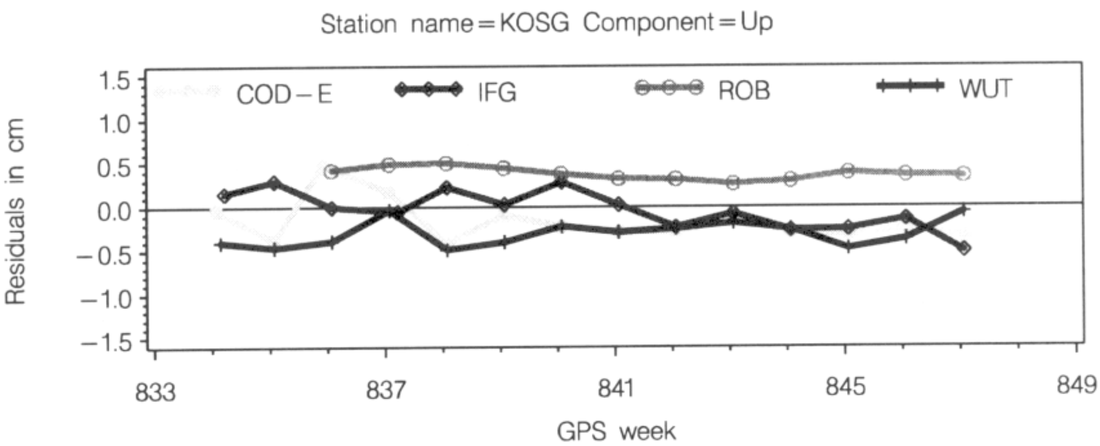

Fig. 3: Residuals in vertical direction for site KOSO.

The agreement in the horizontal components is even better. Systematical differences in the heights (the ROB solution is about 1.0 cm off) may occur for "small" networks if troposphere parameters are estimated for all sites from the GPS data, only. Such inconsistencies can be widely reduced by introducing in the local networks the troposphere estimates derived ftom the global IGS Analysis Centers (BROCKMANN 1996b). (GENDT 1995) demonstrated the excellent agreement of the troposphere esti- mates between the different IGS Analysis Centers.

A summary of the residuals using all sites is shown in Figure 4 for the north and the up component for each particular week.

If we compute a mean rms from the rms values of each week (Figure 4) we obtain values presented in Table 3.

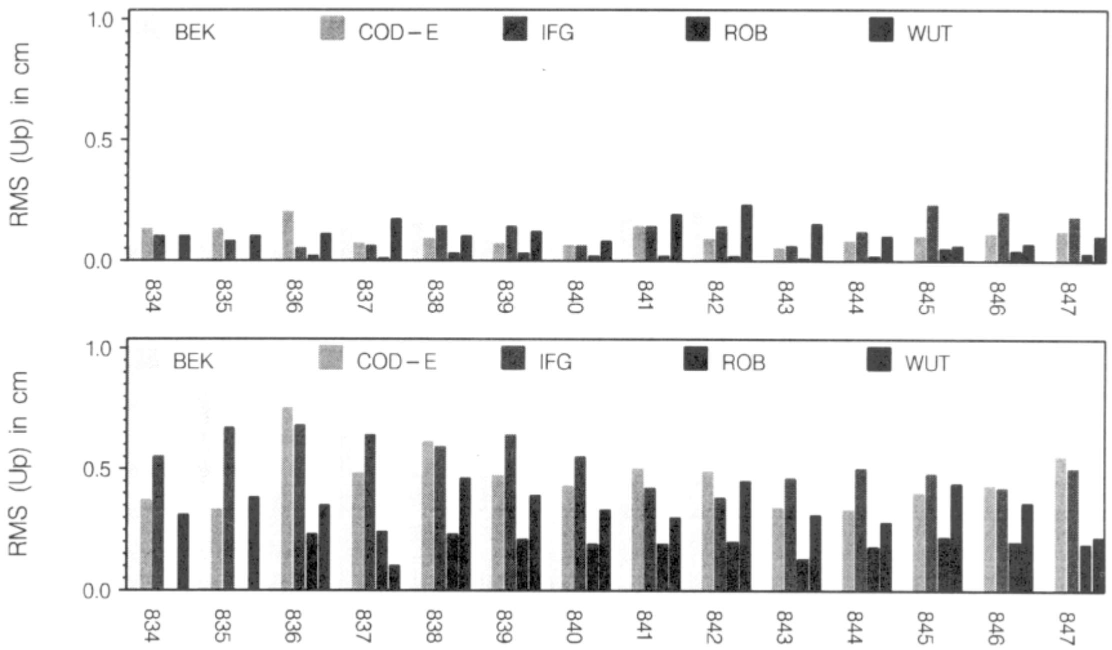

Fig. 4: Unweighted rms values for the components north (a) and up (b) after a 7-parameter Helmert transformation comparing the weekly free Analysis Center results with the weekly combined solution EUR. For the rms computation no sites were excluded.

Tab. 3: Mean rms derived from the comparison between the weekly results with the combined Europen solution EUR. The rms is computed using all weeks and all sites.

Center	# weeks	# sites	component	mean rms in mm
COD-E	14	33	N E U	1.0 1.0 4.6
BEK	9	12	N E U	1.1 1.4 6.0
IFG	12	11	N E U	1.2 1.3 5.3
ROB	12	10	N E U	0.2 0.3 2.0
WUT	12	33	N E U	1.2 1.5 3.3

The agreement between the different solution types is excellent. A comparison of Table 3 with Table 2 shows that the agreement between the different Analysis Centers is about of the same order of magnitude as the week- to-week repeatability of each Analysis Center.

4. Summary and Outlook

In this paper we showed that the concept of a distributed processing works very well in Europe. At present 5 different Analysis Centers process GPS data of permanent tracking sites. The overlap of the processed sites is very high (one Center process e.g. almost all available sites), so that a comparison of the results of the different Analysis Centers is possible. We showed that the agreement between the different Centers is of the same quality as the week-to-week repeatabilities of each Analysis Center.

That shows that with the distributed processing concept the densification of the terrestrial reference frame may be realized with about the same precision as if all sites are processed by a single Analysis Center.

For the consistency of the results it is important, that the different participating Analysis Centers use about the same processing strategies. The most critical topic is the handling of the troposphere, but also the handling of the antenna phase center variations (BROCKMANN 1996b, ROTHACHER 1996b). Both processing strategies affect mainly the station heights. The modeling of the elevation- dependent antenna phase center variations may lead for

the TRIMBLE antennas to discrepancies of up to 10 cm in the heights. Within IGS the use of the new model IGS-01 (ROTHACHER 1996b) is recommended for the processing after July, I (GPS week 860).

Figure 6 shows the weekly report file from the European combinations, which is distributed as feedback to all participating Centers. Please note, that since the Ankara workshop now also the Amalysis Center OLG (Observatory Lustbuehel Graz) joined the club. In near future the *Nordic Geodetic Commission* (NGK) will also be able to provide weekly SINEX results from about 20 nordic sites and the *Italian Space Agency* (ASI, Matera) intends to provide solutions for their Italian permanent GPS networks. Then, with July 1, these European solutions will also be sent to the global Data Centers (CDDIS). That enables the *Global Network Associated Analysis Centers* (GNAACs) to perform a weekly global solution including the EUREF contribution.

References

BEUTLER G., MUELLER I., NEILAN R., WESER R. (1994). The *International GPS Service for Geodynamies (GPS).* Bulletin Géodésique 68(l), 39-70.

Boucher C., ALTAMIMI Z. (1994): IERS *Technical Note 18, Results and Analysis of the ITRF93.* International Earth Rotation Service (IERS), Central Bureau.

BOUCHFR C., ALTAMIMI Z. (1996): *IERS Technical Note 20, Results and Analysis of the ITRF94.* International Earth Rotation Service (IERS), Central Bureau.

BROCKMANN E. (1996): Combination *of Solutionsfor Geodetic and Geodynamic Applications of the Global Positioning System.* Ph. D. thesis, Astronomical Institute, University of Beme.

GENDT G., BEUTLFR G. (1995): Consistency *in ihe Troposphere Estimations Using the IGS network.* In Proceedings of the IGS Workshop in Potsdam on Special Topics and New Directions, May 1 5-17, Potsdam.

HEDLING G., JONSSON B. (1995): SWEPOS - *a Swedish Network of Reference Stationsfor GPS.* In 4th International Conference on Differential Satellite Navigation Systems (DSNS 95), Bergen.

KOCH K. (1*988): Parameter estimation and hypothesis testing in linear models.* Springer, Berlin, Heidelberg, New York.

KOUBAJ. (1995)' *SINEXfonnat version 0.05.* e-mail send to all IGS Analysis Centers, 12. June 1995.

KOUBA J. (1996): SINEX *format deseription version I.0.* e-mail send to all IGS Analysis Centers April 1996.

ROTRACHER M. (1996): Mean *Antenna Phase Offsets and Elevation-Dependent Phase Center Cocrrections.* Submitted by e-mail to all Analysis Centers (July, 1).

Rothacher M., BEUTLER G., GURTNER W., BROCKMANN E., MERVART L. (1993): Documentation *of the Bernese GPS Software Version 3.4.* Astronomical Institute, University of Berne.

WOLF H. (1978): Das *geodätische Gauss-Heimert-Modell und seine Eigenschaften.* Zeitschrift for Vermessungswesen (103),41-43.