Annual Report 1995 of the CODE Analysis Center of the IGS

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1. INTRODUCTION AND OVERVIEW

CODE, the Center for Orbit Determination in Europe, 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), Berne, Switzerland

The CODE Analysis Center, according to its name and the participating institutions, lays special emphasis on *Europe* in two respects:

- The European region is clearly over-represented in the global CODE solutions (about one third of the 75 sites used in the global solutions are European sites). This should guarantee that the CODE orbits are of as good a quality as possible *over Europe.*
- A special solution for approximately 30 European sites is routinely computed with a delay of about 14 days using the final CODE orbits to monitor the European sites and reference frame.

The CODE is located at the AIUB and uses a cluster of DEC Alpha processors for the daily IGS processing. The data is analysed with the Bernese GPS Software Version 4.0.

This report covers the time period from *January 1995* to *April 1996*. During this period the number of sites in "our" global network — and therefore also the number of observations and parameters — was again growing considerably. Table 1 gives an overview of the daily workload at CODE since the beginning of the IGS (test campaign) in June 1992.

Solution Characteristic	Number Used in Daily CODE Processing				
	June 1992	Jan. 1993	Jan. 1994	Jan. 1995	Jan. 1996
Number of Satellites	19	21	26	25	25
Number of Stations	25	28	38	49	72
Number of Observations	50'000	60'000	140'000	210'000	250'000
Total Number of Param.	2'000	2'300	6'000	9'000	12'000
Ambiguity Parameters	1'500	1'800	5'300	8'000	10'500

Table 1. Workload of the Routine 3-Day Solutions at CODE from 1992 to 1996.

Figure 1 shows the number of global sites processed by CODE and the number of parameters in the ambiguity-free and ambiguity-fixed 3-day solutions during the time interval discussed in this report.

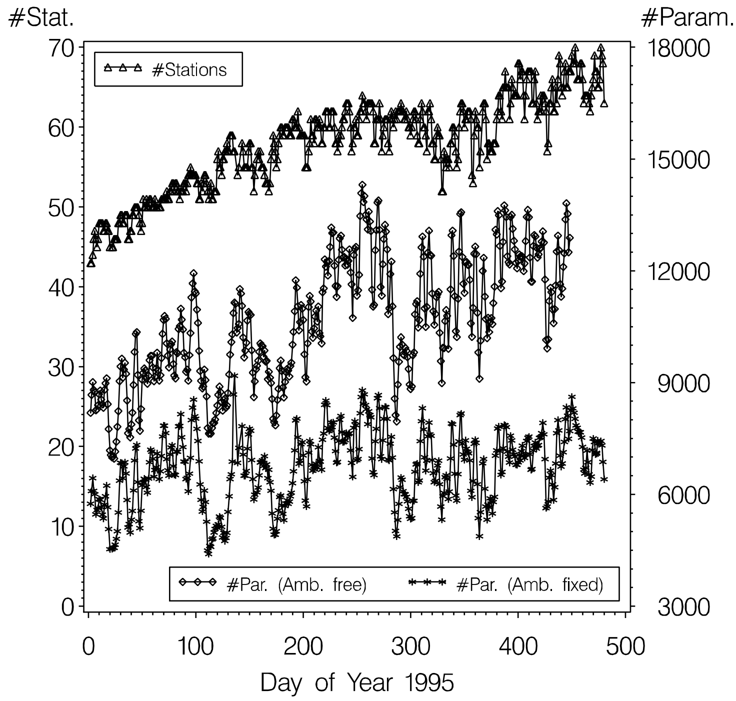

Figure 1. Statistics of Global 3-Day Solutions Computed at CODE

Whereas the number of parameters in the ambiguity-free case is increasing in a similar way as the number of sites, there is no such increase visible in the ambiguity-fixed solutions due to a shortening of the average baseline length in the global network and due to improvements in the ambiguity resolution strategy. On day 084, 1996, the ambiguity-free 3-day solution was discontinued.

Not only the size of the solutions was increasing over time but also the *number of different solutions* produced at CODE: in addition to the solutions already computed day-by-day in January 1995, CODE is now running the ambiguity resolution step and the ambiguity-fixed 1- and 3-day solutions, satellite and receiver clock estimation, a special European solution, ionosphere model computations, rapid orbit solutions, and last but not least an orbit prediction procedure was implemented. The daily processing as it is implemented at CODE at present (April 1996) is outlined in Section 2.

During the last year many new developments were taking place at the CODE Analysis Center. They are described in more detail in the following sections. Table 2 summarizes major changes during the time period covered by this report.

2. DAILY ROUTINE PROCESSING AT CODE

Since January 1, 1996, there are three major processing procedures running at CODE every day: the normal IGS processing (producing the final CODE orbits), the generation of a rapid orbit solution, and the computation of a European solution. A flow chart of the normal IGS routine at CODE is shown in Figure 2 and discussed in detail below. For the rapid IGS procedure only the differences with respect to the normal IGS routine will be discussed.

Figure 3 gives a map of the complete network of 75 stations used for the normal IGS routine analysis at CODE (April 1996).

The routine analysis currently starts at 21:45 local time with the processing of the data that were gathered three day before. The routine processing first checks what data are available — the IGN Global Data Center provides us with the data of the stations we want to process — and tries to download any data, that might still be missing, from CDDIS or SIO, the two other global data centers. Under normal circumstances only a few stations (on average about 4) have to be downloaded in this step.

After the download step all RINEX data (observation and navigation data) are transformed into the Bernese format, the code observations are checked for outliers, and code single point positioning solutions are computed for each station. This single point positioning is used to synchronize the receiver clocks with respect to GPS time. Broadcast ephemerides and clocks are used in this step. This procedure, called "IGSA", takes about 30 minutes of CPU time.

The next part of the routine procedure, called "IGSG", is dedicated to the generation of a global 1-day solution of good quality. In a first step the phase data has to be cleaned. For this step the orbit quality used is essential. Before we started the routine computation of rapid orbits in January 1996, we had to use either orbits predicted from the solutions of previous days or, in case of manoeuvres or modeling problems, the broadcast orbits.

Date	Year/Doy	Description of Change at CODE	Section
01-JAN-95	001/95	Change from the ITRF92 to the ITRF93 coordinate and velocity set for the 13 fixed sites.	3
19-MAR-95	078/95	Pseudo-stochastic pulses set up for the eclipsing satellites at 45 minutes after the exit from the shadow.	4
04-JUN-95	155/95	Estimation of pseudo-stochastic pulses for *all* satellites at 12:00 UT and 24:00 UT (once per revolution).	4
04-JUN-95	155/95	Submission of the first weekly coordinate solution in the SINEX format.	3
25-JUN-95	176/95	Ambiguity-fixed solutions submitted as the official solution.	8
10-SEP-95	253/95	Precise satellite clocks are estimated using code observations and submitted together with the precise orbit files.	5
03-NOV-95	307/95	Station GOLD (Goldstone) not fixed any longer on ITRF coordinates (unknown antenna change).	3
01-JAN-96	001/96	Routine computation of global ionosphere models to support the ambiguity resolution algorithm. Daily global ionosphere models are available starting January 1, 1995 (reprocessing of 1995).	7
01-JAN-96	001/96	Computation of the first rapid orbits with a delay of 12 hours after the observations. These orbits are predicted for two days to obtain real-time orbits.	4
12-JAN-96	012/96	Terrible disk crash.	–
22-JAN-96	022/96	The new radiation pressure model with 9 parameters per satellite implemented in processing, but all parameters constrained to zero with the exception of the conventional ones (direct rad. pressure coeff. and y-bias). Switch from the Rock4/42 S-model to the T-model.	4
24-MAR-96	084/96	Ambiguity-free 3-day solution discontinued.	–
24-MAR-96	084/96	Set-up of subdaily pole and UT1-UTC estimates (offsets and drifts in 2 hour intervals) in the routine solutions for internal purposes.	6
07-APR-96	098/96	A routine test solution making use of the fully new radiation pressure model (except that no x-comp. is estimated).	4
07-APR-96	098/96	A special pole file is created using the rapid pole results to omit large jumps when passing from one Bulletin A file to the next updated version.	–
08-APR-96	099/96	Pseudo-stochastic pulses are set up for all satellites at 12:00 UT for the 1-day solutions to improve the orbit quality. These 1-day orbits are used for ambiguity fixing.	4
09-APR-96	100/96	Rapid orbits are computed with fixed ambiguities.	4

Table 2. Changes/Modifications of Processing at the CODE Analysis Center of the IGS During 1995 and the Beginning of 1996

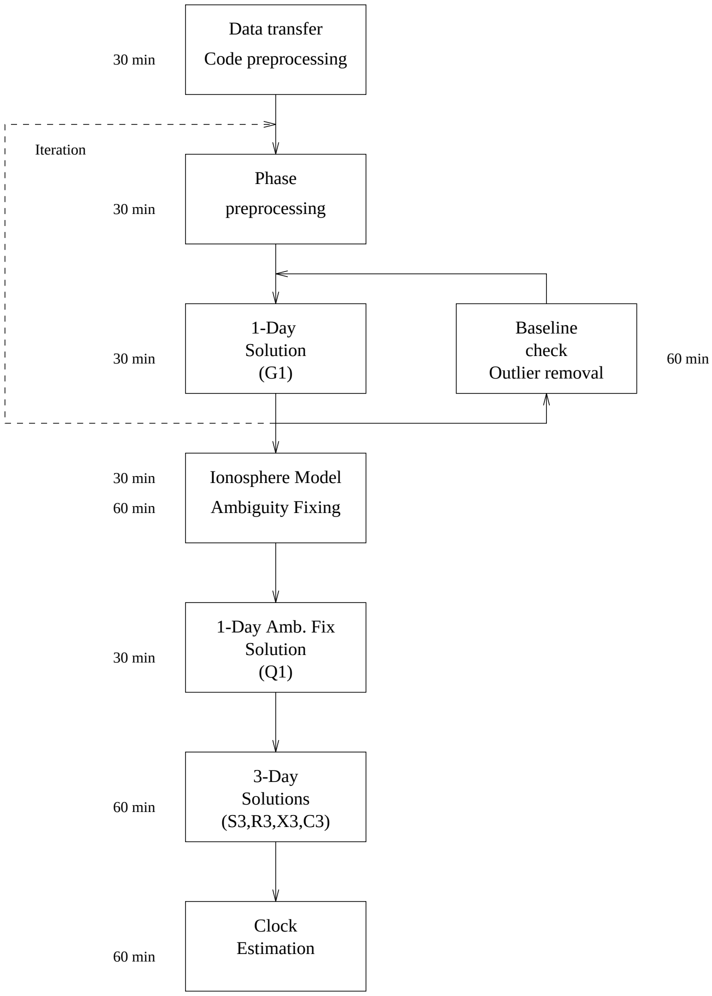

Figure 2. IGS Data Processing Flow at CODE (April 1996).

In both cases it was necessary to perform an iteration to improve the orbit quality (producing a first 1-day solution and then cleaning the phase data a second time with these improved 1-day orbits). Nowadays such an iterative procedure is obsolete because of the high quality of the rapid orbits (manoeuvres have to be dealt with now at the rapid orbit stage). In the 1-day solution (computed after the phase cleaning) we estimate orbit parameters, ERPs (including ERP drifts), station coordinates, and troposphere zenith delays.

Because under AS some receivers (mainly Rogues and some Turborogues) are sometimes producing data with strange systematic biases that are difficult to detect with our conventional pre-processing algorithms, an extra step was added to screen the post-fit residuals of all baselines for outliers. The full 1-day solution is then repeated producing the final 1-day results, labeled G1 (see "Global Solution Types" below). The final 1-day orbits have a quality already comparable to the orbits of the best IGS AC centers, but an improvement is still possible when going to longer arcs, i.e. to 3-day solutions.

The G1-products are made available on our anonymous ftp account as soon as they have been computed (see "Daily Products" below).

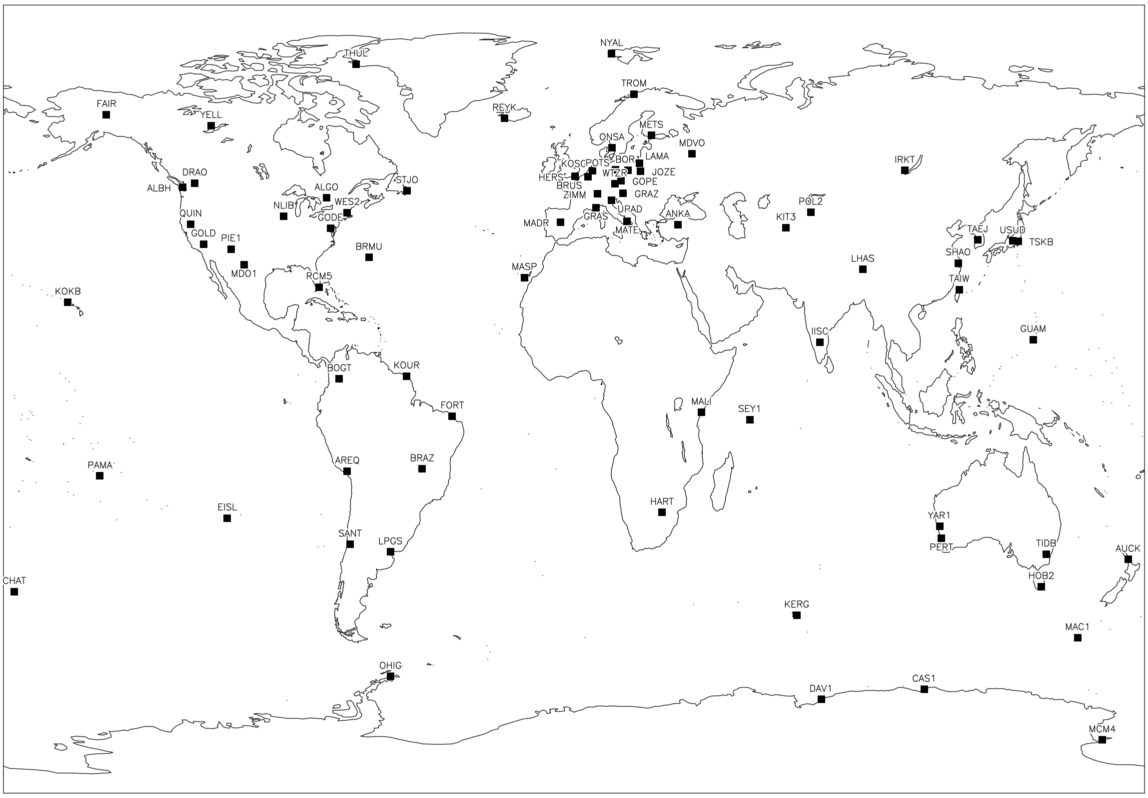

Figure 3. The Global Network of 75 Stations Used in the CODE Routine Analyses.

The complete “IGSG” routine requires about 2.5 hours of CPU time.

The procedure for the 3-day solutions starts with the computation of a global ionosphere model used for the ambiguity resolution step to follow (see Section 7 and 8). After ambiguity fixing (on the single baseline level) a new, complete 1-day solution is generated saving the normal equation information for *all* parameters that might be of interest later on (as e.g. the parameters of the extended orbit model, subdaily ERPs, nutation drifts, center of mass coordinates, satellite antenna offsets, ...). A 3-day solution is then produced combining the normal equations of this last day with the normal equations of the previous two 1-day solutions (see [*Beutler et al.*, 1996] for the algorithms used to combine 1-day arcs into 3-day arcs). Four different 3-day solutions are currently created in this way, labeled S3, R3, X3, and C3 (see ”Global Solution Types” below). Our official IGS products stem from the middle day of the R3-solution. The 3-day solution procedure takes about 3 hours CPU time.

Finally a clock solution is computed where the satellite and station clocks are solved for simultaneously using code observations only. This clock solution is described in detail in Section 5 and takes about 1 hour of CPU time including one iteration and several steps for quality checks.

The complete IGS routine needs about 7 hours of CPU time per day, which means about 10 hours turn-around time.

The Rapid Orbit Computation

Since January 1, 1996, CODE is making available *rapid orbits* with a delay of only 12 hours! The estimation scheme for the rapid orbits is very similar to the normal routine processing up to the 1-day ambiguity-fixed solution. The basic differences are that (a) an iteration is necessary for the orbit improvement, since there is no good a priori orbit information available, and that (b) at present no ionosphere model is estimated and used in the ambiguity resolution step. The final rapid orbit solution is a *5-day solution* with 5-day satellite arcs in contrast to the 3-day arcs in the normal procedure. For these 5-day solutions the 9 radiation pressure parameters of the extended orbit model are set up and solved for.

The most important difference from the operational point of view is, however, that the rapid orbits are generated using the *Bernese Processing Engine (BPE)*, a tool for the fully automated processing of permanent networks, which allows a parallel processing on many CPUs. The ambiguity resolution step e.g., which is done baseline by baseline, is run on 6 different machines simultaneously. This reduces the processing time considerably because it makes optimal use of the 6 DEC Alpha stations available at our university. Instead of 10 hours (normal IGS procedure) the generation of the rapid orbits takes about 3 hours turn-around time. With such a strategy the processing time only grows linearly with the number of stations, i.e. a network of about 100 stations might be processed in 4 hours.

The European Solution

Apart from the normal and the rapid IGS procedures CODE also generates a European solution. This solution — Figure 4 shows a map of the network — is computed with a delay of about 2 weeks making use of the official CODE products (orbits and ERPs).

Figure 4. European Network of 35 Stations Processed at CODE with a Delay of two Weeks.

It was mainly set up for test purposes. With this regional network we can in a first step check the quality of our orbits, then use it to test new processing strategies, and finally gain experiences in how a typical IGS "customer" should make use of the IGS products to achieve the highest possible precision and how the regional solutions may be combined with the global solutions (densification issues).

The stations `CAGL, EBRE, HFLK, PENC, KELY, KIRU, MEDI, NOTO, SFER, VILL`, and `ZWEN` are included *only* in this European solution providing an independent check of our orbit quality, whereas all other sites are also part of the global CODE solution.

The series of European solutions is combined with the series of global solutions for the annual submission to the ITRF Sub-bureau of the IERS.

Global Solution Types

Several different solution series are routinely generated at the CODE Analysis Center (see also Figure 2), although only one official series is submitted to the global data centers:

G1-Series: Since June 21, 1992, our final 1-day solution. Precise ephemerides files, earth rotation parameters, and station coordinates are saved. The orbits and ERPs are available on our anonymous ftp account until we have completed our official 3-day solution. Older results are available on request.

Q1-Series: Q1 designates the ambiguity-fixed 1-day solution series. Although the computation of Q1-solution started on June 25, 1995, we began only recently to save the results of this solution type.

R3-Series: Starting June 25, 1995 (GPS week 807), this is the official CODE solution delivered to the global data centers. The satellites are modeled using our conventional 8 parameter orbit model. In addition, five small velocity changes (pseudo-stochastic pulses) per satellite are estimated over the 3-day arc in the radial and along-track directions. The earth orientation parameters are estimated as a first degree polynomial over the three days. Four troposphere zenith delays are determined per station and day.

S3-Series: The S3-series only started on April 7, 1996. But due to the reprocessing of 1995 (including S3-solutions) almost a full year of S3-solutions is available. The S3-series is identical to the R3-series with the exception of the ERP estimation: instead of one first degree polynomial over three days we estimate subdaily pole and UT1-UTC values in 2-hour intervals (see Section 6).

X3-Series: This solution type was started together with the S3-series on April 7, 1996, and was also included in the reprocessing of 1995. This solution determines a subset of the parameters of the extended orbit model (the "X"-terms are heavily constrained, see Section 4). Apart from this the X3-series is identical to the R3-series.

C3-Series: This series is produced since January 1, 1994. It includes the estimation of the nutation drift corrections in longitude $\Delta\psi$ and obliquity $\Delta\varepsilon$ (in addition to the other ERPs). All other characteristics are identical to the R3-Series (except that before April 7, 1996, the C3-series was based on ambiguity-free solutions).

Daily Products

On the anonymous ftp account CODE makes available several of its (IGS) products (*ftp ubeclu.unibe.ch -or- 130.92.6.11, after login: cd aiub$ftp*).

The anonymous ftp area is divided into two product directories: the directory `CODE` containing our official IGS products and the Bernese Software user directory `BSWUSER` with Bernese-specific information like daily coordinates and troposphere estimates.

```
BSWUSER --- ATM        CODE --- 1992
        |-- DATPAN           |-- 1993
        |-- GEN              |-- 1994
        |-- OUT              |-- 1995
        |-- STA
```

The subdirectories of the `CODE` directory contain the products of the past years. Some of the products in these annual directories have been compressed using the standard compression algorithms used by the IGS (e.g. for RINEX file compression). The data of the current year is located (in uncompressed form) directly in the `CODE` directory. A summary of the products available on our anonymous ftp is given in Table 3.

Daily Products	
`CODwwwwd.EP1`	CODE 1-day orbits (G1-series). Available with a 3-day delay
`CODwwwwd.ER1`	CODE 1-day ERPs (G1-series) belonging to the 1-day orbits
`CODwwwwd.ERH_R`	CODE rapid orbits. Available with a 12-hour delay
`CODwwwwd.ERP_R`	CODE rapid ERPs belonging to the rapid orbits
`CODwwwwd.EPH_P`	CODE 24-hour orbit predictions
`CODwwwwd.ERH_P2`	CODE 48-hour orbit predictions
Weekly Products	
`CODwwwwd.EPH`	CODE final orbits (R3-series). This is our official orbit product!
`CODwwwwd.ERP`	CODE final ERPs (R3-series) belonging to the final orbits
`CODwwww7.SUM`	CODE weekly summary file
`CODwwww7.SNX`	CODE weekly SINEX file
`CODwwwwd.ION`	CODE daily global ionosphere model, Bernese format
`CODwwwwd.CLK`	CODE satellite clock estimates (5 min. sampl.), Bernese format
`B1_yyddd.CLK`	Broadcast satellite clock information, Bernese format
BSWUSER Subdirectories	
`ATM`	Contains the troposphere estimates of the R3-series
`DATPAN`	Contains some files specific to the Bernese software
`GEN`	Official IERS poles (C04 and Bulletin A) in the Bernese format and some additional files for the Bernese software
`OUT`	Contains the ERP estimates of the R3-series
`STA`	Contains the coordinate estimates of the R3- and the European series

Table 3. CODE Products Available Through Anonymous FTP.

3. COORDINATES AND VELOCITIES

With the beginning of the year 1995 the CODE Analysis Center introduced, in agreement with all other Analysis Centers of the IGS, the *ITRF93* (IERS Terrestrial Reference Frame) as the new reference for the computation of the daily products (orbits and ERPs). The system is realized by tightly constraining the coordinate and velocity values of the 13 IGS core sites to the ITRF93 values in the daily solutions.

A consequence of the change from ITRF92 to ITRF93 is a discontinuity in the x- and y-coordinates of the pole; the LOD estimates are not affected. Based on normal equations we reprocessed all the solutions back to September 1993 to determine the impact of the system change [*Brockmann*, 1996]. A comparison of the two series (ITRF92 and ITRF93 as reference frame) over a time interval of about 1.5 years gives the following results:
At epoch 1993.0 we see an offset in the x- and y-pole of about -0.15 $\pm$ 0.06 mas and -0.85 $\pm$ 0.08 mas respectively. The drift difference of -0.45 $\pm$ 0.06 mas/yr in the x-pole and -0.40 $\pm$ 0.05 mas/yr in the y-pole can be attributed to the differences between the two velocity fields (alignment with NNR-NUVEL1 for ITRF92 versus alignment with the C04 pole drift for ITRF93).

In Table 4 we compared the IGS core sites of a CODE 2.75-year solution with ITRF92 and ITRF93 using a 7-parameter Helmert transformation. The epoch of comparison is August 1994. The improvement in the consistency between the GPS solution of CODE and the ITRF is mainly a consequence of the fact that GPS contributed considerably to the ITRF93 solution.

ITRF92			ITRF93		
North	East	Up	North	East	Up
12.1	12.0	23.9	4.7	4.3	11.7

Table 4. RMS of a 7-Parameter Helmert Transformation Comparing the 13 IGS Core Sites of the CODE 2.75-Year Solution with the Values of ITRF92 and ITRF93.

The 2.75-year solution, mentioned above, was submitted to the IERS in April 1996 in the SINEX format (Software Independent Exchange Format) as the CODE 1995 contribution to the ITRF. A total of 102 sites are included in this solution. Site velocities were estimated for 58 sites (using the information of 69 site occupations).

As a new product (starting with GPS week 804) weekly site coordinate solutions are computed at CODE from 3-day solutions (combination of three non-overlapping 3-day solutions). The weekly results are reported to the global data centers in the SINEX format. Such weekly solutions of all the IGS Analysis Centers are then combined and compared by the Global Network Associated Analysis Centers (GNAAC) as part of the IGS Densification Pilot Project.

To study the quality of our weekly coordinate estimates we analyzed the repeatabilities in baseline length of weekly solutions in 1993, 1994, and 1995. The quantity "baseline length" is well-suited for this purpose because of its invariance with respect to the reference frame definition. The velocities estimated from 2.75 years of GPS observations were used to take into account the linear motion of the sites within the time period analyzed.

Assuming that the baseline length repeatability σ_L may be written as a linear function of the baseline length L:

$$\sigma_L\ [mm] = a\ [mm] + b\ [ppb] \cdot L\ [1000\ km]. \tag{1}$$

we obtain the values listed in Table 5 for the three years.

Year (Interval)	# Baselines (# Stations)	Repeatability a [mm]	Repeatability b [ppb]
1993 (0.75 yrs)	383 33	0.09	2.96
1994 (1.0 yrs)	520 44	1.07	2.00
1995 (1.0 yrs)	765 65	1.77	1.41

Table 5. Repeatability for the Baseline Length Determined from Weekly Free GPS Solutions.

Substitution of these values into formula (1) shows that a mean precision of 3 mm in baseline length may be expected for e.g. typical baselines in Europe of 1000 km using one week of continuous GPS observations. A considerable improvement from 1993 to 1995 can be seen for long baselines. A 6000 km baseline (e.g. between Europe and North America) was determined with a precision of approximately 18 mm in 1993 and with about 10 mm in 1995. The improvement in the results is mainly a consequence of the increasing number of global IGS sites, the better geographical distribution, and the improvements in the processing strategies at the CODE Analysis Center.

The excellent agreement between the weekly results of different Analysis Centers is demonstrated by the IGS reports of the three *Global Network Associated Analysis Centers* and is not discussed here.

In Figure 5 we would like to address the problem of the station height estimation in the case of a mixture of different antenna types.

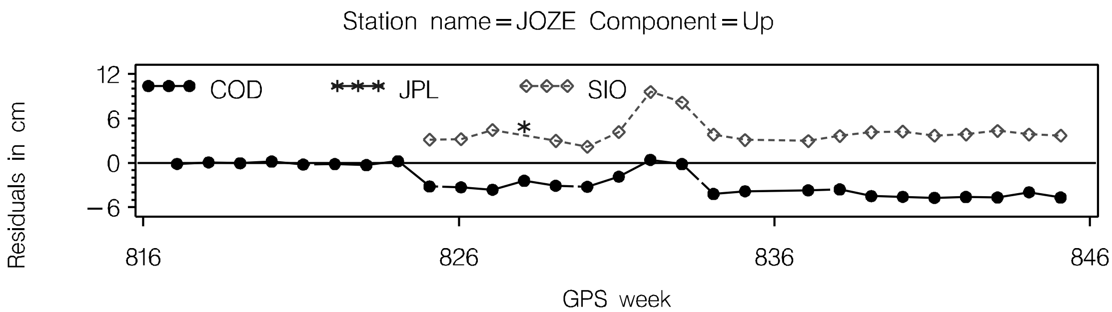

Figure 5. Comparison of Station Height Estimates for the Site JOZE Derived from the Weekly SINEX Contributions of the IGS Analysis Centers.

Depending on how elevation-dependent antenna phase center variation are modeled, large differences may be seen between the height estimates of the individual IGS Analysis Centers (see Section 9). The reason of the discrepancy between the CODE heights on one hand and the SIO heights on the other hand resdies in the fact that SIO does *not* apply elevation-dependent phase center variations for the Trimble antennas (relative to the Dorne Margolin antennas).

4. ORBIT MODELING IMPROVEMENTS

During the first months of 1995 it became more and more evident that the orbit model used at CODE was not sufficient to represent the satellite trajectories over a 3-day period, even for satellites not passing through the Earth shadow. Figure 6 compares five different orbit estimation strategies

1. 1-day arcs without the estimation of pseudo-stochastic pulses
2. 1-day arcs with 2 stochastic pulse per revolution (one in radial "R", the other in along-track direction "S")
3. 3-day arcs without pseudo-stochastic pulses
4. 3-day arcs with 2 stochastic pulses per revolution
5. 3-day arcs with 3 stochastic pulses per revolution (including an additional pulse per revolution in the out-of-plane direction "W")

by fitting a 7-day arc through 7 individual 1-day or 3-day solutions (middle days only) using the CODE Extended Orbit Model (9 radiation pressure parameters instead of 2, see [*Beutler et al.*, 1994]). The improvement due to the estimation of pseudo-stochastic pulses is pronounced in the case of 3-day solutions.

Seeing this, the estimation strategy for pseudo-stochastic pulses was changed on June 4, 1995 (see also Table 2): whereas up to this date pseudo-stochastic pulses were only set up for the *eclipsing satellites*, such pulses were now estimated for *all* satellites. This new strategy considerably improved the CODE orbit quality.

In January 1996 the Extended CODE Orbit Model with a maximum of 9 radiation pressure parameters per satellite and arc — only used so far with satellite positions as pseudo-observations (e.g. in the long arc comparisons done by the Analysis Center Coordinator) — was fully implemented into the parameter estimation and normal equation stacking programs [*Springer et al.*, 1996]. The full radiation pressure model may now be estimated using the phase (and code) observations directly. The final CODE products are still based on the conventional radiation pressure model, although all 9 radiation pressure parameters are set up for later use.

Reprocessing about 8 months of the year 1995 with the Extended CODE Orbit Model gave us a sufficiently long series of solutions to obtain more information on how this new model may be optimally tuned for the routine CODE processing.

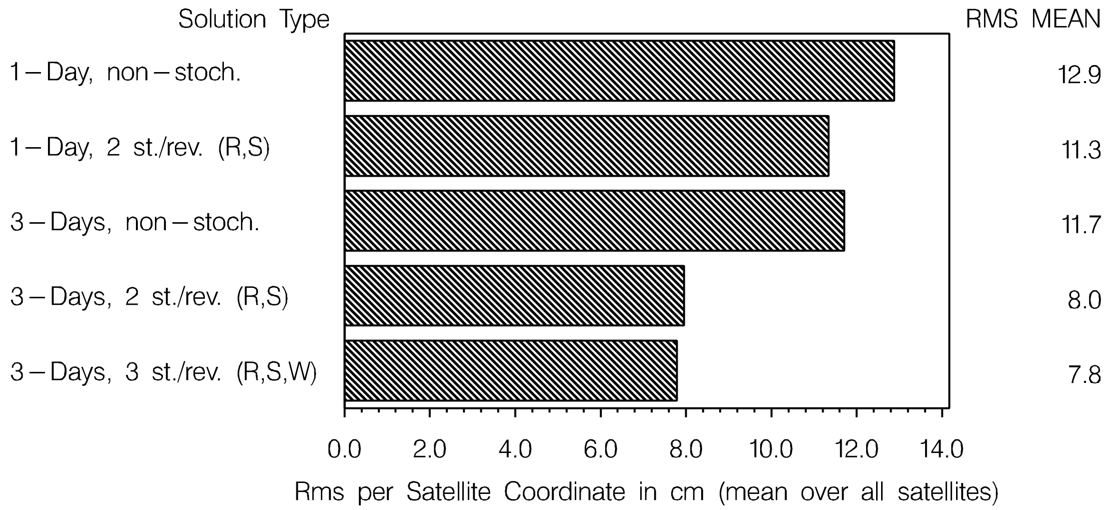

Figure 6. Comparison of Orbit Estimation Strategies by fitting a 7-Day Arc Trough the 7 individual 1- or 3-day solutions of GPS Week 765 Using the Extended CODE Orbit Model.

The new model is already in daily use for two other IGS applications at CODE that started in January 1996: the rapid orbit determination and the orbit predictions.

The rapid orbit procedure used at CODE has already been described in Section 2 and the quality of this new product — available 12 hours after the observations — may be seen in the weekly IGS reports of the rapid orbit combination. In the orbit prediction scheme the rapid orbit results from the last three days are fitted using 3-day arcs. These arcs are then extrapolated for two days thus making predicted orbits available for real-time applications. The quality presently achieved is about 30 cm for 1-day predictions and about 80 cm for 2-day predictions (needed for real-time applications). Both products (the CODE rapid orbits and the orbit predictions) are available at CODE since January 1, 1996 (see Table 3).

During the last year some research was performed at CODE concerning the correlations between ERPs and orbital parameters with the goal to improve the quality and stability of the UT1-UTC and nutation drifts determined from global GPS data. First results concerning the correlation between UT1-UTC, the pseudo-stochastic pulses, and the conventional two radiation pressure parameters (direct coeff. and y-bias) were presented in [*Rothacher et al.*, 1995*c*]. A more general approach (including also nutation parameters) may be found in [*Rothacher et al.*, 1996].

5. SATELLITE CLOCK ESTIMATION

Since September 10, 1995 (GPS week 818) precise satellite clocks are routinely determined at CODE and reported to the IGS global data centers in the precise orbit format. The procedure to estimate the satellite and station clocks is the last part of our IGS routine processing. It consists of five steps.

First a reference clock has to be selected because not all (receiver and satellite) clocks can be estimated. We normally use the receiver clock at Algonquin as time reference. If the Algonquin data are not available another station connected to a hydrogen maser frequency standard is automatically selected. This reference clock is then aligned to GPS time by estimating offset and drift with respect to the broadcast satellite clock values.

In the second step, the actual clock estimation, all good code observations are processed simultaneously to estimate all satellite and station clocks except the clock of the selected reference station. We currently use code measurements only (no phase observations) and only from receivers which are not affected by AS-related biases in the code observations. No Rogue receivers, but most of the Turborogue and all Trimble receivers are included. For the clock estimation we use our "final" orbits, ERPs and coordinate results to guarantee that the clock estimates are consistent with the other final CODE products.

The estimated satellite clocks are then used in the third step to compute a code single point positioning solution for each station contributing to the clock estimation. This aloows us to detect and remove outliers and, if necessary, to repeat the actual clock estimation.

A similar single point positioning solution (step 4) — estimating only offset and drift for each receiver clock instead of epoch-wise clock corrections — allows us check whether the reference clock had a jump sometime during the day and shows us which stations have good external oscillators connected to the GPS receivers.

In the fifth and last step a code single point positioning, but now using *all* available code data (including the data from stations with code biases), is done to verify the code quality of *all* receivers. In this last step we use a cut-off angle of 20 degrees. In all other steps the cut-off angle is set to 30 degrees to avoid the effects of code multipath.

The quality of the CODE satellite clock estimates is of the order of 1-2 nsec (according to the weekly reports on IGS orbit combination, where the satellite clock results are combined and compared, too).

6. EARTH ROTATION PARAMETERS AND NUTATION

The quality of the daily ERP values obtained from the CODE 3-day solutions is now of the order 0.1–0.2 *mas* for the x- and y-pole components and about 0.02 *msec* for LOD. This can be seen from the monthly and weekly IGS reports of the IERS Central Bureau and IERS Rapid Service Sub-bureau.

At CODE we are also routinely estimating — in the special solution series C3 (see Section 2) — the drifts of the nutation in longitude $\Delta\psi$ and obliquity $\Delta\varepsilon$. The a priori nutation model introduced for all the global CODE solutions is the IAU 1980 model, i.e. no correction terms as e.g. given in [*McCarthy*, 1995] are taken into account. The estimated nutation drifts are therefore corrections with respect to the IAU 1980 model. A series of such nutation drifts is available from April 22, 1994, up to now, covering a time interval of almost two years. It is clear that GPS cannot contribute to the long-periodic nutation terms, but it might give contributions to a future nutation model in the high frequency domain. As examples the spectra obtained from the daily estimated nutation drifts in obliquity and in longitude are shown here in Figure 7 covering periods from 3 to 12 days.

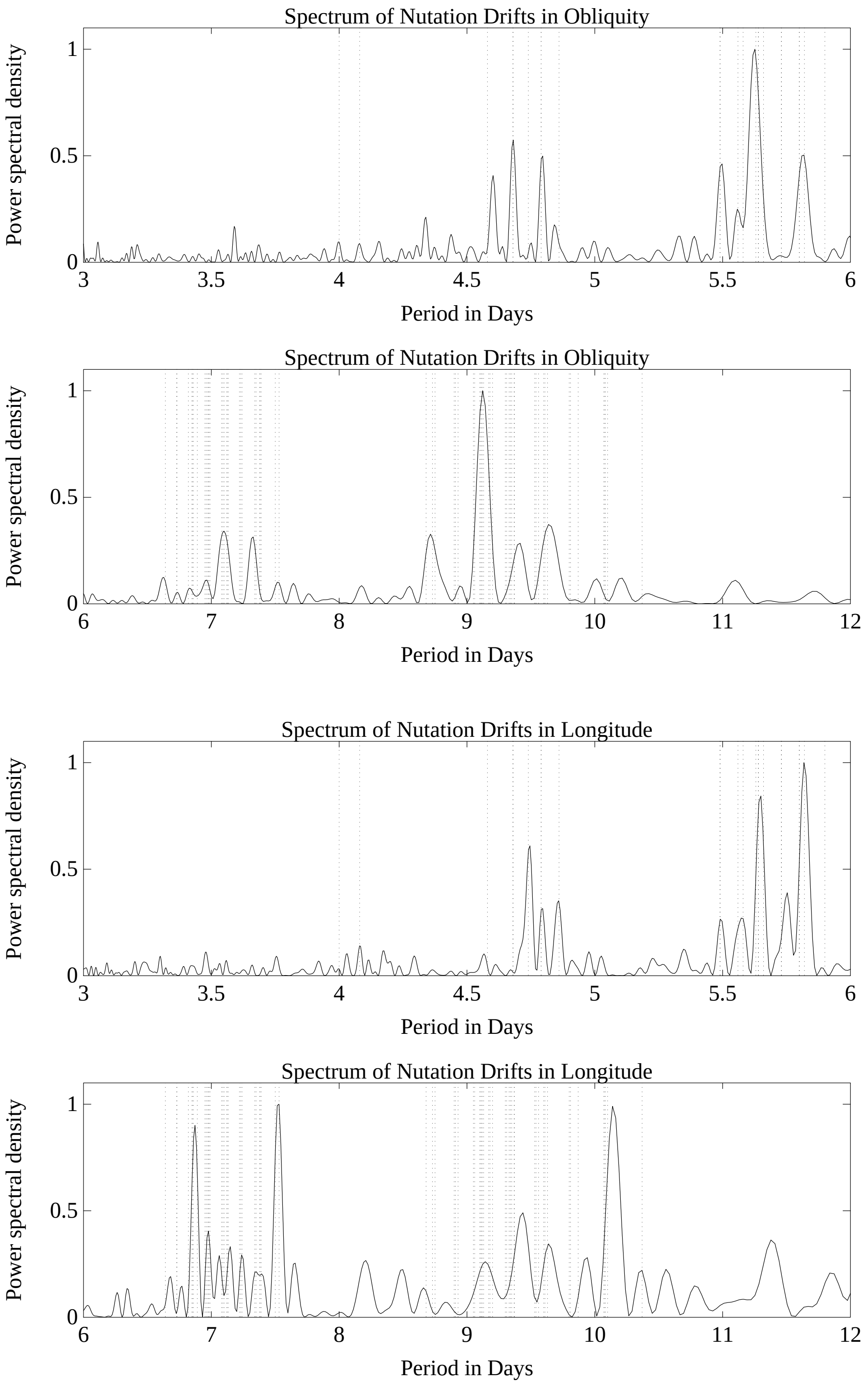

Figure 7. Spectrum of Nutation Corrections in Obliquity and Longitude Derived From the CODE Results in the Time Interval from April 1994 to January 1996.

The dotted vertical lines mark the known nutation periods (e.g. given in the IERS Standards [*McCarthy*, 1992]). In a next step the nutation drift series will be analysed to obtain the amplitudes of the most important correction terms that may then be compared to theoretical and VLBI-derived models. A first GPS nutation model was presented at the XXI. General Assembly of the IUGG in Boulder [*Weber et al.*, 1995].

After having processed several time periods (CONT'94 and CONT'95 campaigns, and a 3-month period in fall 1995) with the estimation of subdaily ERPs for test purposes, we are now routinely setting up ERPs (pole x- and y-coordinates, and UT1-UTC) in 2-hour bins, i.e. as a linear function over 2 hours, enforcing continuity at the interval boundaries. For the official CODE results, these 2-hourly parameter sets are reduced to just one set over the three days of a 3-day solution. At present no a priori model for the subdaily ERP variations is included in the CODE solutions and the results reported to the IERS and IERS Sub-bureau are not containing any subdaily corrections . (The values reported for noon each day are the mean values over one day averaging the subdaily variations).

Based on the saved daily normal equation systems a special solution — called S3 in Figure 2 — is produced to estimate the subdaily variations. This S3-series was started on March 22, 1996. Thanks to the reprocessing effort the same solution type (S3) is available for all days since day of year 127 in 1995. This time series should allow a detailed study of the subdaily ERP variations that can be obtained from a global GPS network. First results were presented by [*Weber et al.*, 1995] and [*Springer et al.*, 1995].

7. GLOBAL IONOSPHERE MAPPING

As shown in [*Schaer et al.*, 1995] it is possible to produce reasonable Global Ionosphere Maps (GIMs) by analyzing of the geometry-free linear combination of double-difference phase observations. We are fully aware of the fact that by using *double* instead of *zero* differences we loose part of the ionospheric signal, but we have the advantage of *clean* observations (no code biases). In addition we are *not* affected by Anti-Spoofing (AS).

Since January 1, 1996 (see Table 2 and Figure 2), the GIM estimation procedure is running in an operational mode. Several GIM products are computed every day:

- Ambiguity-free 1-day GIMs are estimated right prior to the ambiguity resolution step. These GIMs are subsequently used to improve the resolution of the initial carrier phase ambiguities on baselines up to 2000 kilometers.
- Improved GIMs (ambiguity-fixed, with single-layer heights estimated) are derived after the ambiguity resolution step.

At present, the GIM files containing the TEC coefficients for one day are available with a delay of 4 days. These files are copied weekly to our anonymous ftp server.

The global TEC distribution is represented over 24 hours by spherical harmonics up to degree 8 in a geographical reference frame which is co-rotating with the *mean* Sun. A single-layer model is adopted in this approach assuming a spherical ionospheric shell in a height of 400 kilometers above the Earth's mean surface. To extract the global TEC information a separate least-squares adjustment of the observations of the complete IGS network is performed using an elevation cut-off angle of at present 20 degrees. Note that — even under

AS — *no* restrictions concerning receiver types or satellites have to be made in our approach. An example of a 1-day GIM representing an average TEC distribution is shown in Figure 8.

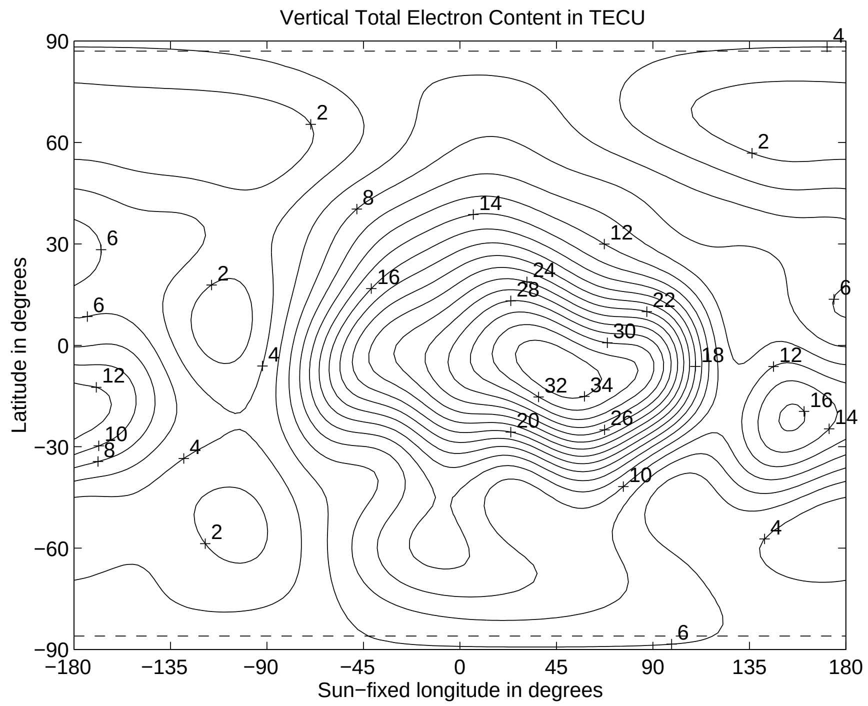

Figure 8. Global Ionosphere Map (GIM) for Day 073, 1996, Plotted in a Sun-Fixed Coordinate System.

After reprocessing all IGS data of the year 1995 and gathering all GIMs already produced in 1996, we may present a long-time series of global TEC parameters [*Schaer et al.*, 1996]. Two special TEC parameters, namely the maximum and the mean TEC, roughly characterizing the deterministic part of the ionosphere, are shown in Figure 9.

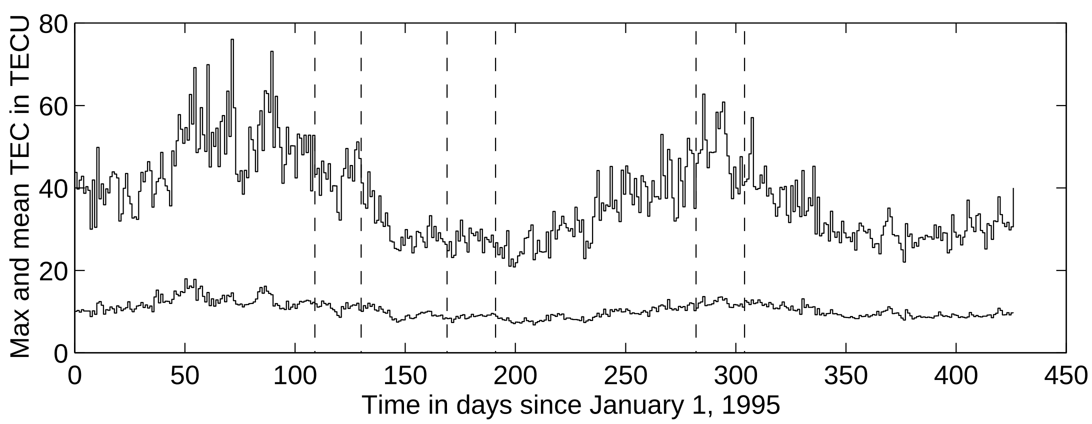

Figure 9. *Maximum* and *Mean* TEC Values Extracted from the Daily CODE GIMs

The three non-AS periods in 1995 are marked by dashed lines.

Let us mention that we also generate *regional* ionosphere maps for Europe based on about 30 European IGS stations in a fully automatic mode since December 1995. These ionosphere maps are used in the processing scheme of the European cluster to support the ambiguity resolution there. The European TEC maps are available on special request.

8. GLOBAL AMBIGUITY RESOLUTION

Since June 25, 1995 (GPS week 807) — after an experimental phase of several months — the *ambiguity-fixed* 3-day solutions are submitted to the IGS as official CODE contribution. We perform ambiguity resolution on baselines up to 2000 kilometers using the so-called Quasi-Ionosphere-Free (QIF) ambiguity resolution strategy [*Mervart*, 1995], which allows ambiguity resolution on long baselines without using code measurements. Since January 1, 1996, the QIF strategy is supported by GPS-derived global ionosphere models [*Schaer et al.*, 1996]. At present we resolve about 85 % of the ambiguities referring to baselines below 2000 kilometers, that means that on average about 50 % of *all* ambiguities can be fixed on their integer values (see also Figure 1). Figure 10 shows the percentage of resolved ambiguity parameters on baselines shorter than 2000 kilometers. We may recognize (a) three significant peaks caused by AS-free periods and (b) on January 1, 1996, a jump of about 10 % when we started to use our 1-day GIMs.

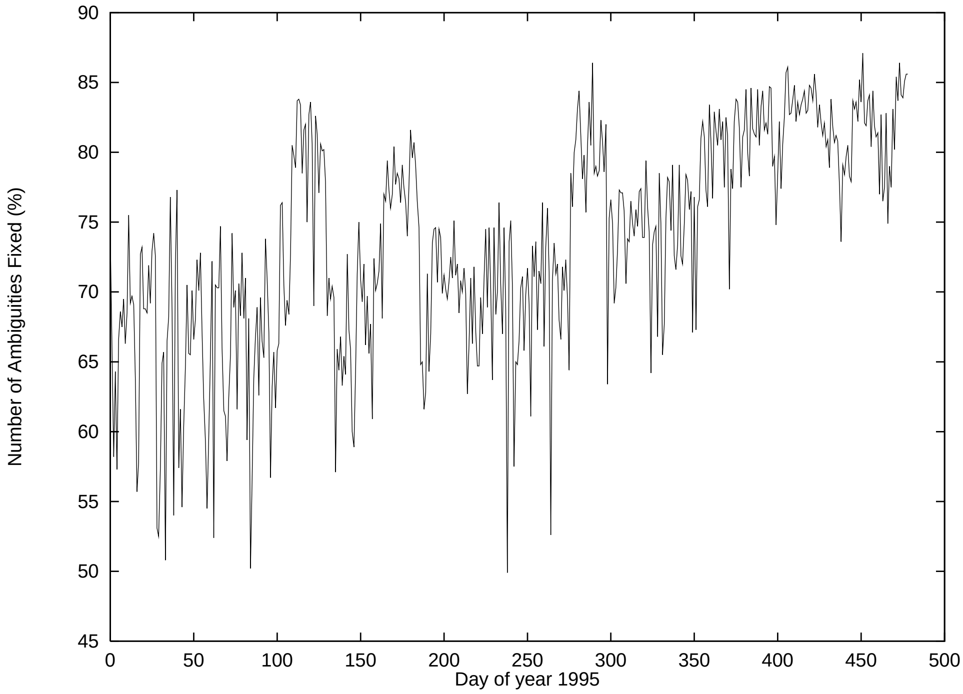

Figure 10. Percentage of Ambiguities Fixed on Baselines Below 2000 km.

The effect of resolving ambiguities in a global network has been discussed in [*Mervart et al.*, 1995].

9. ANTENNA PHASE CENTER CALIBRATIONS

The importance of the antenna phase center calibrations for the IGS network can be seen from the example given in Section 3, Figure 5.

During the last year two GPS antenna calibration campaigns were processed at the AIUB to compute elevation-dependent phase center variations:

- The *THUN-94 Campaign*
- The *WETTZELL-95 Campaign*

The antenna types calibrated during these campaigns were `DORNE MARGOLIN T` and `B` (Turborogue, Rogue), `4000ST L1/L2 GEOD` (SN14532, Trimble), `TR GEOD L1/L2` (SN22020, Trimble), `SR299E EXTERNAL` and `SR299 INTERNAL` (Leica), and `GEOD L1/L2 P` (SN700228, Ashtech).

The results show that the phase center variations estimated from GPS data are very consistent, even between different campaigns with different local environments (multipath).

For the L1 frequency the agreement between the GPS results and the results of recent UNAVCO chamber tests [*Rocken et al.*, 1996] is very promising, not so, however, for the L2 results, where some problems still wait for a solution.

The estimation strategy, the models used, and results have been published in [*Rothacher et al.*, 1995*b*], [*Rothacher et al.*, 1995*a*], and [*Rothacher and Schaer*, 1996].

The elevation-dependent phase center corrections used in the CODE processing are listed in Table 6.

PHASE CENTER OFFSETS INCLUDING ELEVATION DEPENDENCE USED AT CODE

RECEIVER TYPE	FREQ	PHASE CENTER OFFSETS (M)			ELEVATION DEPENDENCE OF PHASE CENTER (MM)																
ANTENNA TYPE	L*	NORTH	EAST	UP	90	85	80	75	70	65	60	55	50	45	40	35	30	25	20	15	10
******************	*	**.****	**.****	**.****	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**
ROGUE SNR-8	1	0.0	0.0	0.0779	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DORNE MARGOLIN B	2	0.0	0.0	0.0964	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ROGUE SNR-8	1	0.0	0.0	0.0779	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DORNE MARGOLIN R	2	0.0	0.0	0.0964	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ROGUE SNR-8100	1	0.0	0.0	0.1100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DORNE MARGOLIN T	2	0.0	0.0	0.1280	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TRIMBLE 4000SSE	1	0.0	0.0	0.0692	0	1	3	7	10	13	15	16	18	17	16	15	12	11	10	9	8
4000ST L1/L2 GEOD	2	0.0	0.0	0.0677	0	0	2	3	3	4	5	5	7	7	6	7	7	6	7	7	6
TRIMBLE 4000SSE	1	0.0	0.0	0.0625	0	1	3	7	10	13	15	16	18	17	16	15	12	11	10	9	8
TR GEOD L1/L2 GP	2	0.0	0.0	0.0625	0	0	2	3	3	4	5	5	7	7	6	7	7	6	7	7	6
TRIMBLE 4000SSE	1	0.0	0.0	0.0700	-4	-4	-4	-3	-2	-2	-1	0	1	1	1	0	-1	-1	-1	0	8
M-PULSE L1/L2 SUR	2	0.0	0.0	0.0900	-3	-2	0	0	-1	0	0	0	1	1	1	0	1	1	1	1	-5

Table 6. Antenna Phase Center Corrections Used at the CODE Analysis Center Since 1993

The offsets are given relative to the "Antenna Reference Point" as defined by the IGS (for antenna names and antenna sketches see the files `ANTENNA.GRA` and `RCVR_ANT.TAB` at the IGS Central Bureau Information System described in [*Gurtner and Liu*, 1995]). The elevation-dependent corrections for the Trimble antennas (relative to the Rogue antennas!) were introduced into the routine processing on July 20, 1993, and are stemming from old chamber measurements by [*Schupler et al.*, 1994], the values for the Trimble micropulse antenna were introduced in April 1996 (for the EBRE site) and were computed at the AIUB from GPS calibration measurements.

A new and improved set of consistent calibration values are currently put together from various sources by a small group and should be implemented by the IGS Analysis Centers by June 30, 1996.

References

Beutler, G., E. Brockmann, W. Gurtner, U. Hugentobler, L. Mervart, and M. Rothacher (1994), Extended Orbit Modeling Techniques at the CODE Processing Center of the International GPS Service for Geodynamics (IGS): Theory and Initial Results, *Manuscripta Geodetica*, *19*, 367–386, April 1994.

Beutler, G., E. Brockmann, U. Hugentobler, L. Mervart, M. Rothacher, and R. Weber (1996), Combining consecutive short arcs into long arcs for precise and efficient gps orbit determination, *Journal of Geodesy*, *70*, 287–299.

Brockmann, E. (1996), *Combination of Solutions for Geodetic and Geodynamic Applications of the Global Positioning System (GPS)*, Ph.D. dissertation, Astronomical Institute, University of Berne, Berne, Switzerland (in preparation).

Gurtner, J., and R. Liu (1995), The Central Bureau Information System, in *IGS 1994 Annual Report*, edited by R. Liu J.F. Zumberge and R.E. Neilan, pp. 43–57, IGS Central Bureau, Jet Propulsion Laboratory, Pasadena, California U.S.A., September 1 1995.

McCarthy, D.D. (1992), IERS Standards (1992), *IERS Technical Note 13*, Observatoire de Paris, Paris, July 1992.

McCarthy, D.D. (1995), IERS Standards (1995), *IERS Technical Note (in preparation)*, Observatoire de Paris, Paris, July 1995.

Mervart, L. (1995), Ambiguity Resolution Techniques in Geodetic and Geodynamic Applications of the Global Positioning System, Geodätisch-geophysikalische Arbeiten in der Schweiz, Band 53.

Mervart, L., G. Beutler, M. Rothacher, and S. Schaer (1995), The Impact of Ambiguity Resolution on GPS Orbit Determination and on Global Geodynamics Studies, presented at the XXI. General Assembly of the International Union of Geodesy and Geophysics, Boulder, Colorado, July 2–14 1995.

Rocken, C., C. Meertens, B. Stephens, J. Braun, T. VanHove, S. Perry, O. Ruud, M. McCallum, and J. Richardson (1996), Receiver and antenna test report, UNAVCO Academic Research Infrastructure (ARI).

Rothacher, M., and S. Schaer (1996), Processing of GPS Antenna Calibration Campaigs at AIUB Using Double-Difference Phase Observations, presented at the IGS Analysis Center Workshop, NOAA, Silver Spring, USA, March 19–21 1996.

Rothacher, M., W. Gurtner, S. Schaer, R. Weber, W. Schlüter, and H.O. Hase (1995*a*), Azimuth- and Elevation-Dependent Phase Center Corrections for Geodetic GPS Antennas Estimated From GPS Calibration Campaigns, in *International Association of Geodesy Symposia, Symposium No. 115: GPS Trends in Precise Terrestrial, Airborne, and Spaceborne Applications*, edited by G. Beutler *et al.*, Springer, Boulder, CO, USA, July 3–4 1995.

Rothacher, M., S. Schaer, L. Mervart, and G. Beutler (1995*b*), Determination of Antenna Phase Center Variations Using GPS Data, in *IGS Workshop Proceedings on Special Topics and New Directions*, edited by G. Gendt and G. Dick, pp. 77–92, GeoForschungsZentrum, Potsdam, Germany, May 15–18 1995.

Rothacher, M., G. Beutler, and L. Mervart (1995*c*), The Perturbation of the Orbital Elements of GPS Sattelites Through Direct Radiation Pressure, in *IGS Workshop Proceedings on Special Topics and New Directions*, edited by G. Gendt and G. Dick, pp. 152–166, GeoForschungsZentrum, Potsdam, Germany, May 15–18 1995.

Rothacher, M., G. Beutler, and T. A. Springer (1996), The Impact of the Extended CODE Orbit Model on the Estimation of Earth Rotation Parameters, presented at the IGS Analysis Center Workshop, NOAA, Silver Spring, USA, March 19–21 1996.

Schaer, S., G. Beutler, L. Mervart, M. Rothacher, and U. Wild (1995), Global and Regional Ionosphere Models Using the GPS Double Difference Phase Observable, in *IGS Workshop Proceedings on Special Topics and New Directions*, edited by G. Gendt and G. Dick, pp. 77–92, GeoForschungs-Zentrum, Potsdam, Germany, May 15–18, 1995.

Schaer, S., G. Beutler, M. Rothacher, and T.A. Springer (1996), Daily Global Ionosphere Maps Based on GPS Carrier Phasa Data Routinely Produced by the CODE Analysis Center, presented at the IGS Analysis Center Workshop, NOAA, Silver Spring, MD, USA, March 19–21, 1996.

Schupler, B.R., R.L. Allshouse, and T.A. Clark (1994), Signal Characteristics of GPS User Antennas, Preprint accepted for publication in Navigation in late 1994.

Springer, T.A., G. Beutler, M. Rothacher, and E. Brockmann (1995), The Role of Orbit Models when Estimating Earth Rotation Parameters using the Global Positioning System, *presented at the AGU Fall Meeting, EOS Transactions*, *76*(46), 60, November 7 1995.

Springer, T.A., M. Rothacher, and G. Beutler (1996), Using the Extended CODE Orbit Model: First Experiences, presented at the IGS Analysis Center Workshop, NOAA, Silver Spring, USA, March 19–21 1996.

Weber, R., G. Beutler, E. Brockmann, and M. Rothacher (1995), Monitoring Earth Orientation Variations at the Center for Orbit Determination in Europe (CODE), presented at the XXI. General Assembly of the International Union of Geodesy and Geophysics, Boulder, Colorado, July 2–14 1995.