Annual Report 1997 of the CODE Analysis Center of the IGS

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1. INTRODUCTION

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 Federal Agency of Cartography and Geodesy (BKG), Frankfurt, Germany,
- the Institut Géographique National (IGN), Paris, France, and
- the Astronomical Institute of the University of Berne (AIUB), Berne, Switzerland.

CODE is located at the AIUB. All solutions and results are produced with the latest version of the Bernese GPS Software [*Rothacher and Mervart*, 1996].

This report covers the time period from *May 1997* to *June 1998*. It focuses on the major changes in the routine processing during this period and shows the new developments and products generated at CODE. The processing strategies used *till April 1997* are described in the annual reports of previous years ([*Rothacher et al.*, 1995], [*Rothacher et al.*, 1996*a*], and [*Rothacher et al.*, 1997*a*]).

Figure 1 shows the number of global IGS stations and the number of double-difference phase observations processed at CODE for each day in the time interval from January 1997 to June 1998.

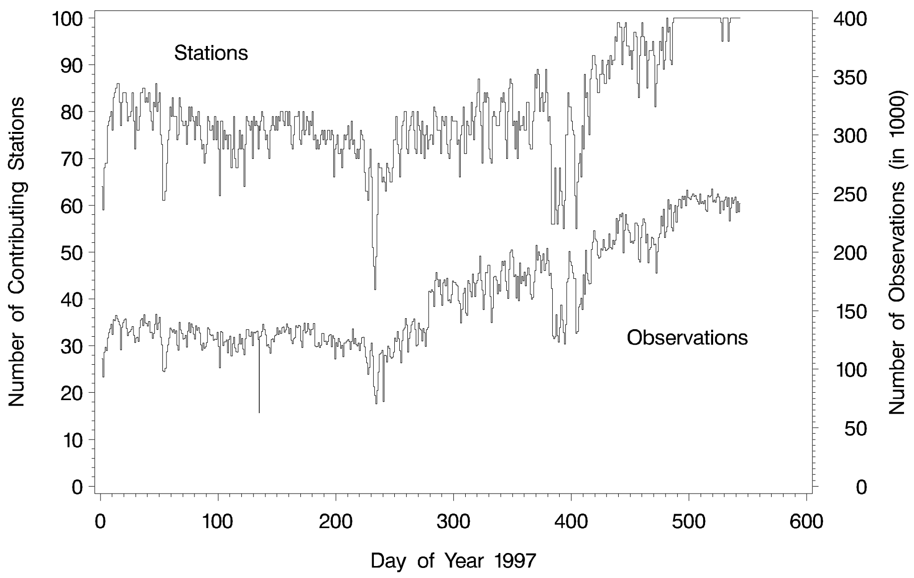

Figure 1. Statistics of the global 1-day solutions computed at CODE.

The number of stations increased from about 80 to 100. An upper limit of 100 for the number of sites to be processed has been set in May 1998. If there is data available from more than 100 sites, the sites with long data gaps are removed first and then sites are selected according to their importance and data quality. The number of observations shows a jump in October 1997 (day 278), where the elevation cut-off angle for the global data processing was changed from 20 to 10 degrees (see Section 3.1 for more details). Due to this processing change and due to the increase in the number of sites with time the number of observations has roughly doubled from January 1997 to June 1998. The significant decrease in the number of stations and observations in February 1998 was caused by a computer problem at one of the operational centers and clearly shows that backup components are needed for such cases.

2. CHANGES IN THE ROUTINE PROCESSING AND PRESENT STATUS AT CODE

The major changes implemented in the CODE routine analysis since May 1997 are listed in Table 3.1. Modifications prior to this date have already been reported in the annual report of last year [*Rothacher et al.*, 1996*a*].

3. PRODUCT QUALITY AND RESULTS

3.1 Change of Elevation Cut-Off Angle

The most significant changes in the last year are related to lowering the elevation cut-off angle from 20 to 10 degrees. Since April 1997, CODE has tested several processing strategies using the data of the permanent European network.

Date	Doy/Year	Description of Change at CODE	Section
23-Sep-97	266/97	Generation of IONEX files containing daily global and European ionosphere maps.	3.8
05-Oct-97	278/97	Major changes of global solutions: elevation cut-off angle set to 10 degrees (previously 20 degrees), Niell dry mapping function for troposphere delays, elevation-dependent weighting of the observations.	3.1
05-Oct-97	278/97	Solid Earth tides according to the IERS Conventions 1996. Polar tides were also included.	—
19-Oct-97	292/97	Troposphere gradient parameters estimated in global 1-day solution for test purposes.	3.7
26-Jan-98	026/98	Maximum degree of spherical harmonics for ionosphere models increased from 8 to 12. A global solution with station-specific ionosphere models using smoothed code observations was set up.	3.8
01-Mar-98	066/98	Switch from ITRF94 to ITRF96. Reference frame defined by 37 sites (of the set of 42 selected by the IGS).	3.2
01-Mar-98	066/98	Ocean loading model according to [*Scherneck*, 1991] implemented (ocean tide maps from [*Le Provost et al.*, 1994]; see also [*McCarthy*, 1996]).	—
01-Apr-98	088/98	2-hour (instead of 24-hour) time resolution for global ionosphere maps. Use of a solar-geomagnetic reference frame for ionospheric modeling.	3.8
06-Jun-98	155/98	In addition to GPS, GLONASS orbit predictions are now routinely produced for the SLR community.	—
11-Jun-98	160/98	1-day and 2-day ionosphere map predictions made available on anonymous ftp at CODE.	3.8
17-Jun-98	168/98	First set of global IONEX files sent to CDDIS.	3.8

Table 1. Modification of processing scheme at the CODE Analysis Center from May 1997 to June 1998.

The cluster of about 40 stations has been processed over many months using eight slightly different processing schemes. The eight solutions differ in the elevation cut-off angle, the tropospheric modeling, and the observation weighting model. More details about these processing strategies may be found in [*Rothacher et al.*, 1997*b*; *Springer et al.*, 1997].

The results of the different European processing strategies clearly indicate that lowering the elevation cut-off angle significantly improves the internal consistency of the station coordinate estimates. This is mainly caused by the better decorrelation of the station heights and the tropospheric zenith path delay parameters (see e.g. [*Rothacher and Beutler*, 1997]). It was also found that it is important to account for the increased noise of the low-elevation data by using an elevation-dependent weighting of the observations. Furthermore, a well performing tropospheric mapping function, e.g. the Niell mapping function [*Niell*, 1993], has to be used.

Based on these European results it was decided to decrease the elevation cut-off angle also for all global solutions, where it had always been set to 20 degrees since the beginning of the IGS in June 1992. A small test series, based on 5-days, was generated using similar strategies as for our European network to verify if the same improvements may be seen in the global solutions. The results of the different tests are summarized in Table 2.

Elev. Cut-Off (deg)	Mapp. Func.	Elev. Weight.	Coord. Repeat. (mm)	Relative to 20^o solution RMS (mm)	Scale (ppb)	#Obs. Inc.(%)	#Param. Inc.(%)
20	Saast.	No	3.10	—	—	—	—
15	Saast.	No	3.10	10.3	−0.7	12	30
15	Niell	Yes	3.06	6.5	−0.1	12	30
10	Saast.	Yes	2.95	10.5	−0.3	23	63
10	Niell	Yes	2.92	5.4	0.9	23	63
5	Saast.	No	3.52	29.3	0.1	26	75
5	Niell	No	3.28	14.4	0.5	26	75
5	Saast.	Yes	3.00	14.9	0.0	26	75
5	Niell	Yes	2.96	9.5	0.9	26	75

Table 2. Results based on global solutions from 5 days using different processing strategies.

Several interesting results can be observed here. First of all, the results clearly deteriorate if the cut-off angle is decreased without proper weighting of the measurements. The results also reveal that the Saastamoinen mapping function [*Saastamoinen*, 1973] is not adequate for low elevation data. Secondly, the amount of data gained is strikingly large; almost a 25% increase can be seen when lowering the elevation cut-off from 20^o to 10^o. Unfortunately, the amount of ambiguity parameters also increases significantly (60–70%), which reflects the higher noise level of the low-elevation data which makes the data cleaning more difficult. Nevertheless, the degree of freedom of the solutions increases significantly (21% when going from 20^o to 10^o). Finally, significant terrestrial scale changes are observed which are depending on the elevation cut-off angle, the weighting of the observations, and the tropospheric mapping function. These scale changes are surprisingly large considering the fact that 9 stations were held fixed to their ITRF94 positions in these tests.

As a result of these tests, the solution using a cut-off of 10^o, with elevation-dependent weights $w = \sin^2 e$, and using Niell's (dry) mapping function was chosen for our global IGS solutions. The 5^o solution was rejected mainly due to the fact that the IGS set of antenna phase center variations (IGS_01) is only valid down to 10^o [*Rothacher et al.*, 1996*b*; *Rothacher*, 1996]. Additional information on the change of the elevation cut-off angle may be found in IGSMAIL #1705 and IGSREPORT #4247. Note that the change of approximately 1 ppb in the scale observed in these tests is still visible in our current official solutions. In a free network solution, the scale change is even more pronounced (2–3 ppb), indicating once more that the scale defined by GPS is not very reliable and heavily depends on the processing strategy and modeling.

3.2 Change of Terrestrial Reference Frame

On March 1, 1998 (GPS week 0947), the IGS changed its realization of the terrestrial reference frame by switching from ITRF94 to ITRF96. At the same time, the set of the 13 "fixed" reference stations was change. A completely new and much larger set of reference stations was selected because the original set of 13 stations was no longer adequate to accurately realize the terrestrial reference frame for the IGS products. From this newly selected set of 48 reference stations CODE selected 36 stations. One more station (REYK)

Sol. ID.	Amb. Fixed	Ele. Cut.	Mapp. Func.	Elev. Wgt.	Repeatability N	E	U	Remarks
EG_	No	15	Saast.	No	2.1	2.6	5.7	Ambig. free
EQB	Yes	15	Saast.	No	1.9	1.9	5.6	Ambig. fixed
NMF	Yes	15	Niell	No	1.9	1.9	5.8	Niell mapping
NMW	Yes	15	Niell	Yes	1.7	1.7	5.5	Elev.dep.weighting
EQ_	Yes	10	Niell	Yes	1.8	1.7	4.9	Cut-off angle 10^o
ET_	Yes	10	Niell	Yes	1.7	1.7	4.5	Global trop. intro.
NM5	Yes	5	Niell	Yes	1.8	1.8	4.8	Cut-off 5^o
NMG	Yes	5	Niell	Yes	1.7	1.7	4.8	Tropo. gradients

Table 3. Overall repeatability of the daily European solutions at CODE based on days 060–157 of 1998. Repeatabilities are given in millimeters.

was added to this list. The ITRF96 positions of these 37 stations are constrained to 1 mm in our official solutions.

Although ITRF94 and ITRF96 nominally have the same orientation and origin, some small effects of the reference frame change were observed in the IGS products, namely, a small rotation around the Earth's Z-axis of about 0.3–0.4 mas and a small change in the Y-coordinate of the pole of about 0.2 mas. More information about these changes may be found in IGSMAIL #1829 and #1838 and IGSREPORT #4698. The change to ITRF96 and the use of the much larger set of reference stations significantly improved the CODE products, in particular the earth rotation parameters ERPs). The precision of the ERP estimates are now below the 0.1-mas level (see IGSMAIL #1853 for details).

3.3 The European Network Solution

Besides being one of seven IGS Analysis Centers, CODE also plays an essential role in the maintenance and densification of the European Reference Frame (EUREF). 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 combined EUREF solution. Each of the EUREF AACs processes a certain subset of available permanent GPS sites in Europe. The main goal of processing the European network, apart from participating as an EUREF Analysis Center, is to study new processing techniques. Eight types of solutions, each using slightly different processing options, are currently generated each day. Two additional solutions are set up to compute regional ionosphere maps and to monitor the ionospheric activity over Europe.

Table 3 shows the internal consistency of the eight different solutions and gives a short description of the basic differences between the solutions. As expected, the fixing of the initial carrier phase ambiguities to their integer values gives a significant improvement in the east component of the site coordinate estimates. Some small improvements for the north and height components may also be noticed. The main conclusions to be drawn from the "regional" results are, however, that the internal consistency improves if the elevation cut-off angle is decreased — provided that the data is properly weighted. A significant improvement may be seen, too, when tropospheric gradient parameters are estimated, but only for those sites which actually track satellites at low elevations. This is not evident from Table 3 because the repeatabilities listed there are dominated by a few "bad" stations, which provide little or no low elevation data. All stations with low elevation data show a highly significant improvement (up to a factor of 2), if gradients are estimated. The improvement is mainly in the horizontal component but also the height repeatability is slightly better. For more details we refer to [*Rothacher et al.*, 1997*b*; *Springer et al.*, 1997].

3.4 The CODE Solar Radiation Pressure Model

The largest error source in GPS orbit modeling is the impact of solar radiation pressure. Over the last few years many improvements have been made in modeling the orbits of GPS satellites within the IGS. However, most improvements were achieved by increasing the number of estimated orbit and/or solar radiation pressure (RPR) parameters. This increase in the number of estimated satellite parameters weakens the solutions of all estimated parameters. Due to correlations, the additional parameters can cause biases in other estimated quantities like, e.g., the length of day.

A new radiation pressure model was derived by fitting 5-day arcs through all CODE final orbits since 1996. By analyzing the resulting time series of RPR parameters, a model for each of the five estimated parameters was computed. The quality of the model was tested by performing a 7-day fit using this new model and estimating only two RPR parameters: a scale term and the y-bias. Using the ROCK4/42 models the RMS of this 7-day fit was around 75 cm whereas with the new CODE model an RMS of only 6 cm resulted, an improvement by almost an order of magnitude. The new model moreover allows a reduction of the number of orbit parameters that have to be estimated. The CODE model was presented at the 1997 AGU Fall meeting and at the IGS 1998 workshop in Darmstadt. More information may be found in [*Springer et al.*, 1998*a*, 1998*b*] and in IGSMAIL #1842.

3.5 Earth Rotation Parameters

In April 1994, CODE started to estimate nutation rate corrections in longitude and obliquity relative to the IAU 1980 theory of nutation. The series of nutation rate estimates covers by now a time interval of more than 4 years. A detailed analysis of this series by [*Rothacher et al.*, 1998] has shown, that GPS may contribute to the high-frequency part of the nutation spectrum, i.e., for periods below about 20 days. The nutation amplitudes estimated in this range of periods are comparable to the best VLBI results.

The series of 2-hourly ERP estimates, started in January 1995, is another unique product of CODE. The uninterrupted series of 3.5 years of sub-daily ERPs may be used to estimate diurnal and semi-diurnal ocean tide amplitudes. The GPS results derived from this series are of equal quality as the best ocean tide models obtained from altimeter data, from VLBI, and from SLR. A thorough discussion of the high-frequency ERP results from CODE may be found in [*Rothacher*, 1998].

3.6 Time and Frequency Transfer with GPS

In 1991 a common project of the Swiss Federal Office of Metrology (OFMET) and CODE/AIUB was initiated to develop time transfer terminals based on geodetic GPS receivers. The goal is the comparison of time offsets with sub-nanosecond accuracy and frequencies with an accuracy of 10^{-15} over one day for two or more (GPS-external) clocks. The OFMET is amongst others responsible for time and frequency maintenance and dissemination in Switzerland. Within this field of activities, time and frequency transfer over a wide range of distances using many different methods (among other TV methods, GPS common view techniques, etc.) are of primary interest.

The software used for this project is the Bernese GPS Software [*Rothacher and Mervart*, 1996]. The Bernese GPS Software originally was a pure "double-difference" software package. For the time transfer project it was essential to modify the software to allow for zero-difference (undifferenced) and single-difference processing. A first step was made in September 1995, enabling zero-difference processing using code observations. In January 1997, the capability to process the undifferenced *phase* data was built into the software.

It was clear from the start of the project, that optimum use should be made of the GPS code and phase measurements and that only geodetic GPS equipment should be used. The emphasis was put on the comparison of external clocks, as opposed to receiver-internal clocks. Calibration of delays in cables, temperature-dependent delays, etc., were and are of vital interest in the context of the joint OFMET/AIUB project (see Figure 2). Let us mention at this point that the control of these delays is absolutely mandatory for GPS-based time transfer. The corresponding requirements are much less stringent for frequency transfer.

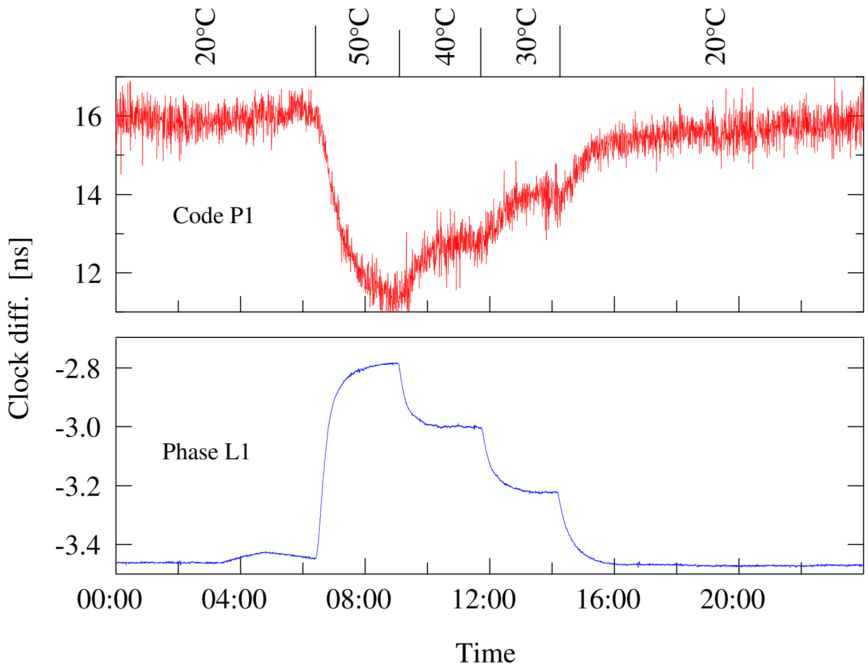

Figure 2. Temperature dependence of the GPS receiver delays for P1 code and L1 phase measurements during one day.

Today two prototype Geodetic Time Transfer terminals (GeTT terminals) are available and a third will be ready in the near future. The terminals contain modified Ashtech Z-12 receivers. More information about the time transfer project and the GeTT terminals may be found in [*Schildknecht et al.*, 1990; *Overney et al.*, 1998]

CODE will participate, in collaboration with the OFMET, in the IGS/BIPM time transfer project. After two experiments on European baselines in 1997 (OFMET-NPL, PTB-NPL), the GeTT terminals will be deployed on a transatlantic baseline during the second half of 1998. This will in fact be the first comparison of the GeTT method with the independent two-way satellite technique (TWSTFT) on an intercontinental baseline.

3.7 Troposphere Gradients

As mentioned in Section 3.3 tropospheric gradients have been estimated in the European solutions of CODE since April 1997 [*Rothacher et al.*, 1997*b*]. In October 1997, a test solution with the estimation of daily troposphere gradients was activated in the *global* CODE processing. Figure 3.7 shows, as an example, the troposphere gradient parameters (excess path delay at 10 degrees elevation angle) of the site Onsala for about 500 days.

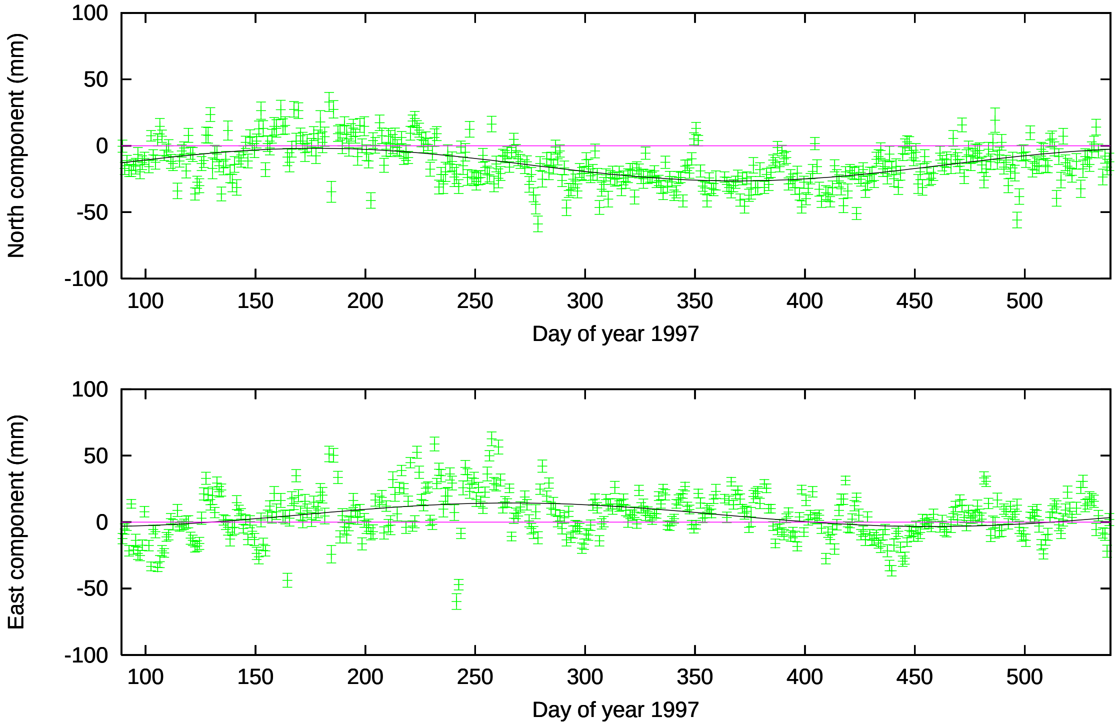

Figure 3. Troposphere gradients for Onsala at 10 degrees elevation.

We recognize a seasonal signature and an offset in both components, especially in the north component. Most sites located on the northern hemisphere exhibit, on the average, significantly larger delays towards the south than the north and vice versa for sites on the southern hemisphere. The same characteristics have also been reported by the VLBI community.

3.8 Ionosphere

At present the following ionosphere products are generated on a routine basis:

- 2-hourly global ionosphere maps (GIMs) are produced using double-difference phase or phase-smoothed code observations. The phase-derived TEC maps proved their usefulness for ambiguity resolution (AR) on long baselines. Rapid global maps are available with a delay of about 12 hours, the final ones after 3 to 4 days.

- Regional (European) maps are produced as well and are also used to support AR. On the average 90% of the initial carrier phase ambiguities can be resolved reliably — without making use of code measurements.

- Daily sets of differential code biases (DCBs) for all GPS satellites (and all contributing receivers) are estimated at CODE since October 1997. The day-to-day scattering of the satellite-specific DCBs is better than 0.1 ns.

- Since June 1998, 1-day and 2-day predicted GIMs are regularly derived. The prediction procedure performed is described in [*Schaer et al.*, 1998*b*].

In order to improve the ionosphere estimation the following changes were made in 1997/1998: The maximum degree of the spherical harmonic (SH) expansion was increased from 8 to 12 to be able to resolve smaller TEC structures like, e. g., the equatorial anomaly. The temporal resolution was increased from 24 hours to 2 hours and slight relative constraints between consecutive sets of SH coefficients were introduced (to get reasonable TEC results for regions where no stations are located). Moreover, we recently refer the SH expansion to a solar-geomagnetic reference frame (instead of a solar-geographic one).

Starting with June 1, 1998, our final GIMs are delivered weekly to CDDIS in compressed IONEX form [*Schaer et al.*, 1998*a*] fulfilling the standards as stated in [*Feltens and Schaer*, 1998]. The CODE IONEX files also contain RMS maps and a set of DCB values for the satellites. Figure 4 shows 12 TEC snapshots of the global TEC for June 1, 1998, referring to times 01:00, 03:00, ..., 23:00 UT. Bright areas indicate low TEC, dark ones high TEC. The dotted line corresponds to the geomagnetic equator.

The long-time series of global TEC parameters available at CODE covers 3.5 years by now and includes up to 1788 SH coefficients per day. The zero-degree coefficient representing the mean TEC on a global scale characterizes the ionospheric activity pretty well. The evolution of this particular TEC parameter during a period of low solar activity is shown in Figure 5. An automatically updated figure showing the complete time series and a one-year prediction of the Earth's mean TEC can be found on the WWW page `http://www.cx.unibe.ch/aiub/ionosphere.html`.

3.9 GLONASS

Since December 1997, a single-frequency receiver (Ashtech GG24) is running permanently at the Zimmerwald observatory. A daily single-point-positioning solution is computed and the time difference between GLONASS time and GPS time is monitored. In Figure 6 we see the systematic difference of about 2 μsec between the time systems (after subtracting the leap seconds of UTC (Moscow)). Also, the difference varies within several ten nanoseconds.

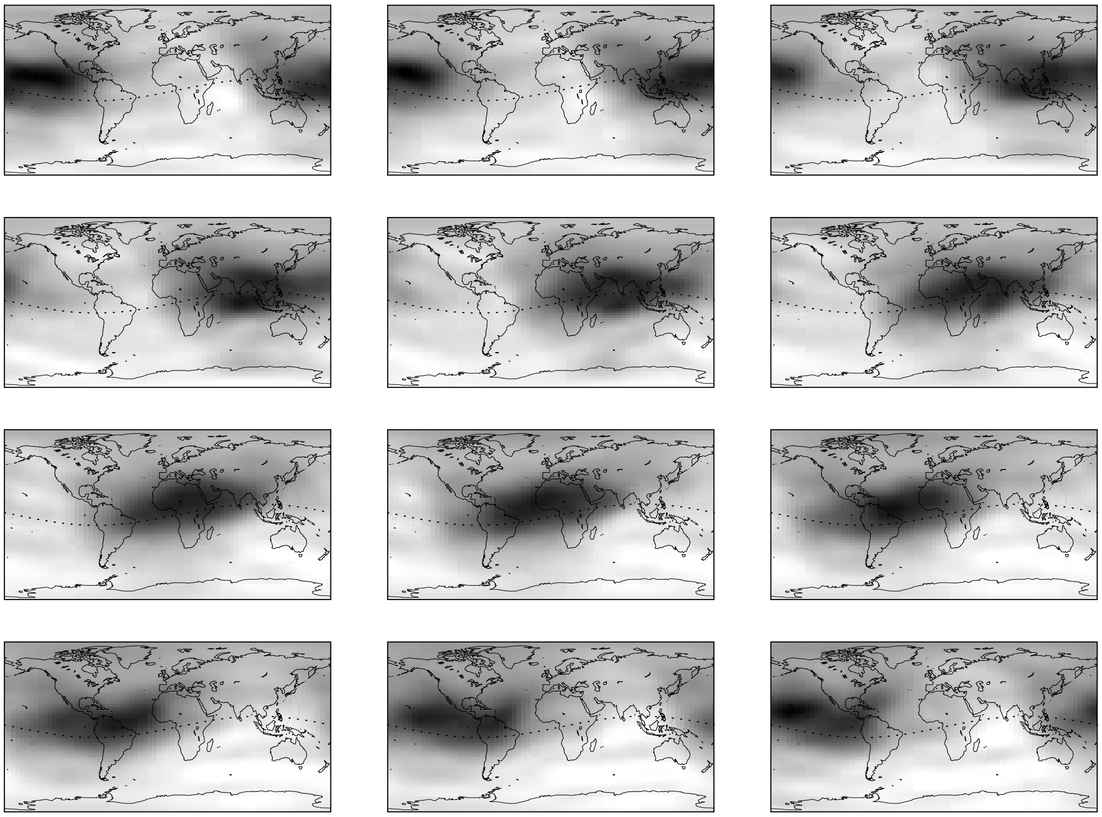

Figure 4. CODE 2-hour GIMs for day 152, 1998

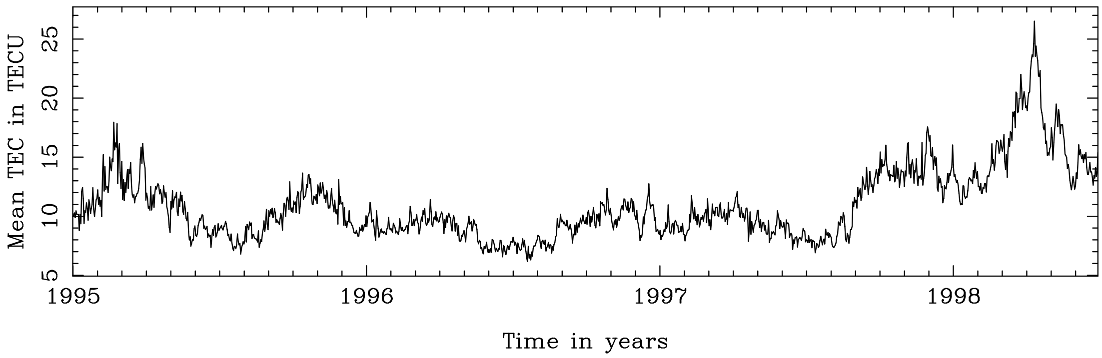

Figure 5. Evolution of the Earth's mean TEC computed by CODE since January 1, 1995

The fit of 3-day arcs through the orbits broadcast by the GLONASS satellites indicate that the precision of the GLONASS orbits is in general 2–3 meters, a quality similar to that of the GPS broadcast orbits. As in the case of GPS, improved GLONASS orbits have to become available in order to make the GLONASS measurements useful for geodetic and geodynamic applications. Presently, the Bernese GPS Software is modified to enable the processing of dual-frequency GLONASS carrier phase data including ambiguity resolution.

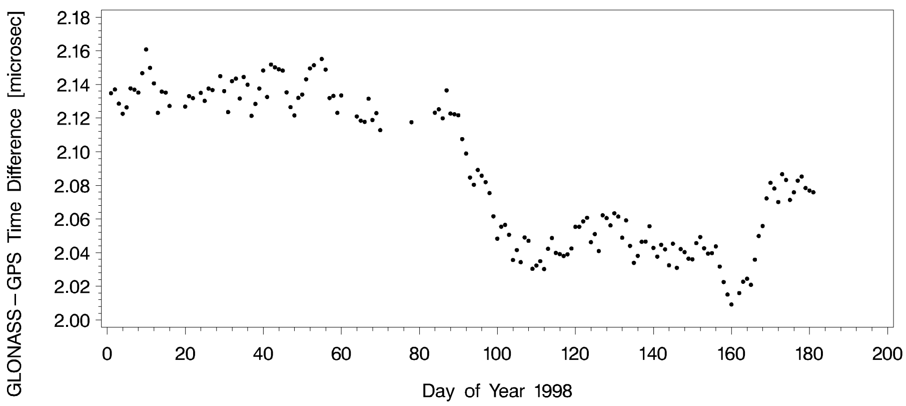

Figure 6. Time difference between the GLONASS and GPS time system.

4. OUTLOOK

For the next year, we plan to realize a combined GPS/GLONASS solution, starting with the activities related to the International GLONASS Experiment (IGEX). It would also be beneficial (especially for tropospheric gradient parameters, that will soon be implemented into the official 3-day solutions) to include data down to 5 degrees elevation, but a new set of antenna phase center calibrations going down to 5 degrees will be needed beforehand. The increase in the amount of data due to the addition of GLONASS and low-elevation data will allow a refined modeling of the troposphere. CODE will continue its special ERP series (sub-daily ERPs and nutation). In view of the present quality of the GPS ERPs and the increasing length of the series, the study of new phenomena in earth rotation (e.g. high-frequency atmospheric normal modes) may become possible. Because sub-daily site displacements are strongly correlated with sub-daily ERPs, a detailed study of ocean loading, atmospheric loading, and short-term variations in site coordinates in general, will be another important field of interest at CODE.

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