Analysis Centers

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1997 Annual Report - 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, 1996a, and 1997a].

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. 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 next sections for more details).

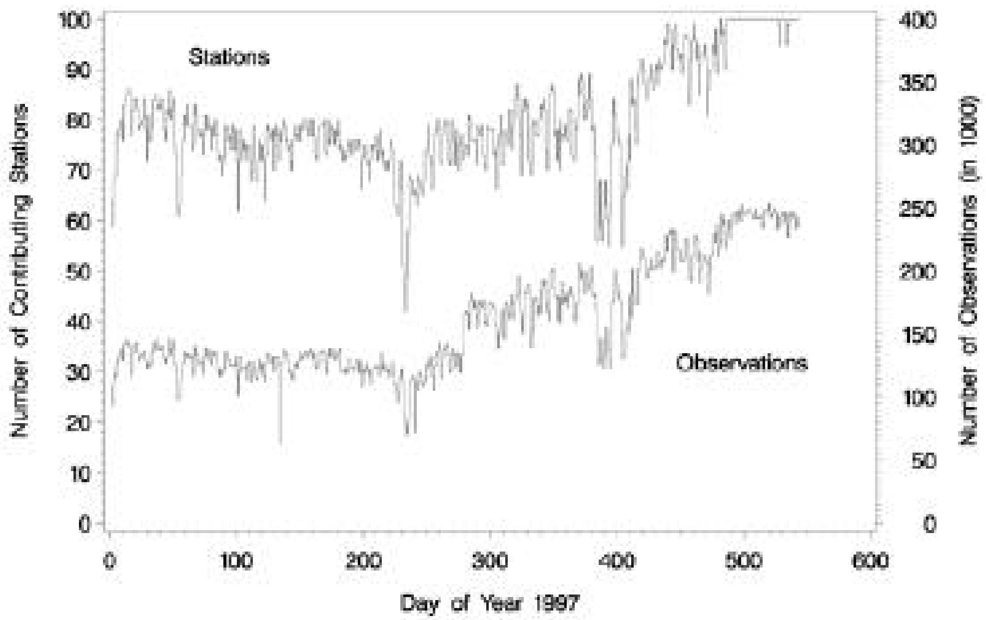

Figure 1. Statistics of the global 1-day solutions computed at CODE

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

The major changes implemented in the CODE routine analysis since May 1997 are listed in Table 1. Modifications prior to this date have already been reported in the annual report of last year [*Rothacher et al.*, 1996a].

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. 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 pro-cessing strategies may be found in [*Rothacher et al*., 1997b; *Springer et al.*, 1997].

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

Date	Doy/Year	Description of Change at CODE
23-Sep-97	266/97	Generation of IONEX files containing daily global and European ionosphere maps.
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.
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.
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.
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).
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.
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.
17-Jun-98	168/98	First set of global IONEX files sent to CDDIS.

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 per-forming 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. There the cut-off 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.

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

Elev. Cut-Off (deg)	Mapp. Func.	Elev. Weight.	Coord. Repeat. (mm)	Relative to 20° 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

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° to 10°. 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° to 10°). 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°, with elevation-dependent weights $w = \sin^2 e$, and using Niell's (dry) mapping function was chosen for our global IGS solutions. The 5° 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° [*Rothacher et al.*, 1996b; *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) 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. 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

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*., 1997b; *Springer et al*., 1997].

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

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°
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°
NMG	Yes	5	Niell	Yes	1.7	1.7	4.8	Tropo. gradients

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.*, 1998a, 1998b] 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. It was originally 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 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.

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.

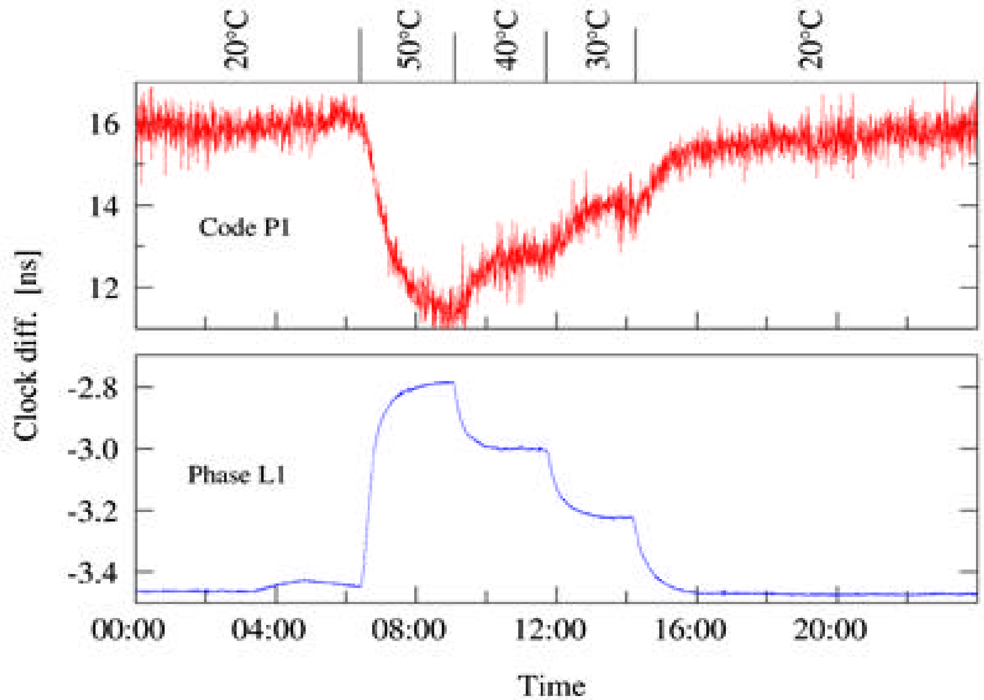

Figure 2. Temperature dependence of the GPS receiver delays for P1 code and L1 phase measurements during one day.

3.7 Troposphere Gradients

As mentioned in a previous section, tropospheric gradients have been estimated in the European solutions of CODE since April 1997 [*Rothacher et al.*, 1997b]. In October 1997, a test solution with the estimation of daily troposphere gradients was activated in the *global* CODE processing. Figure 3 shows, as an example, the troposphere gradient parameters (excess path delay at 10 degrees elevation angle) of the site Onsala for about 500 days.

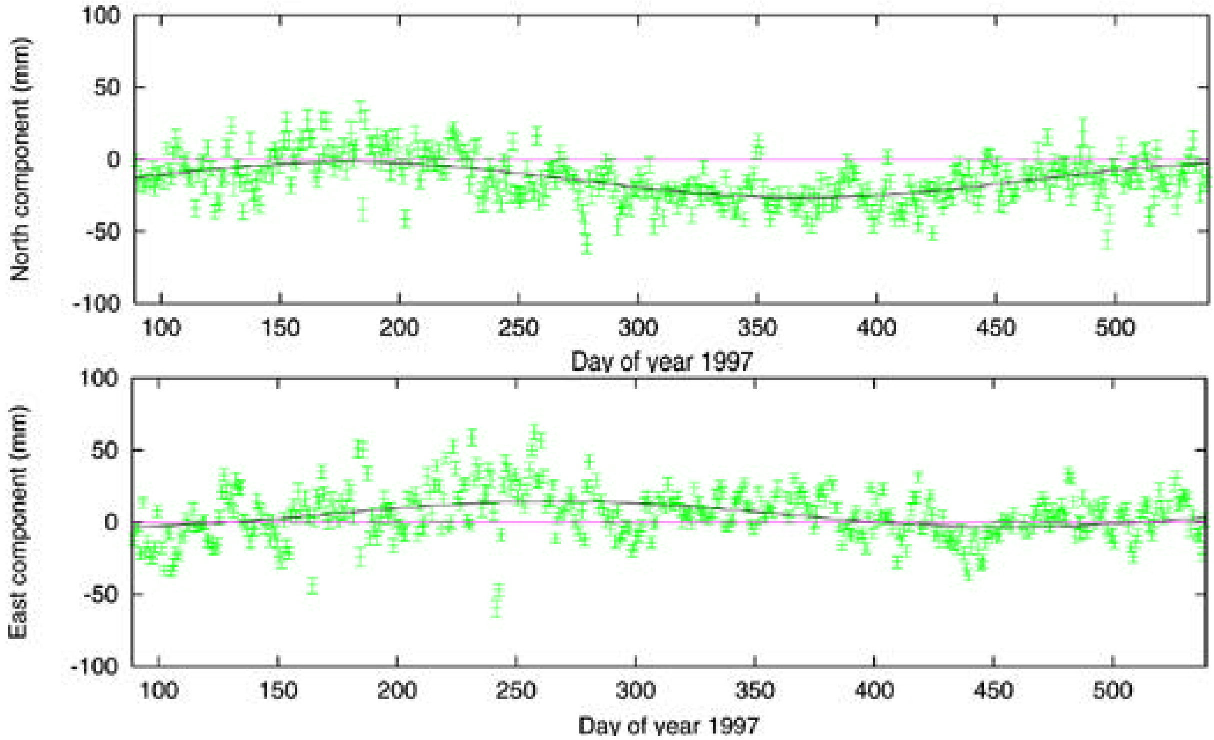

Figure 3. Troposphere gradients for Onsala at 10 degrees elevation.

We recognize a seasonal signature and an offset in both components, especially in the north. 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*., 1998b].

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*., 1998a] 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`.

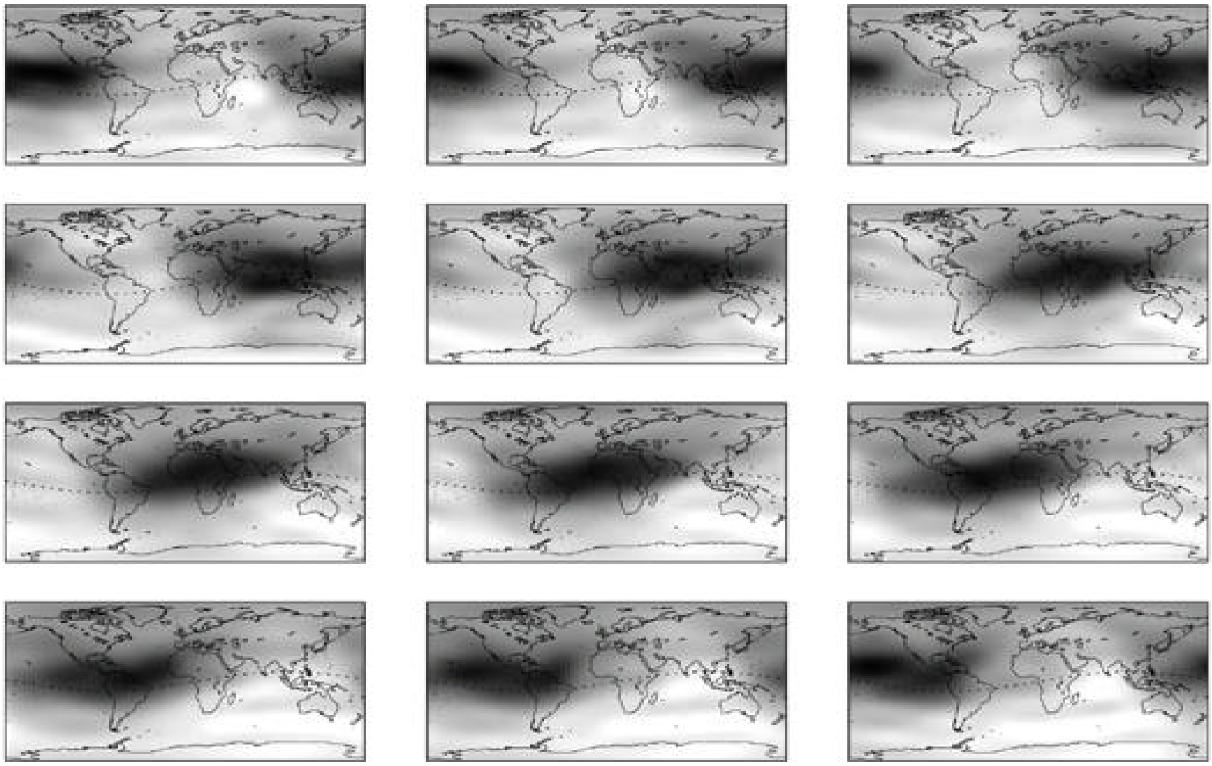

Figure 4. CODE 2-hour GIMs for day 152, 1998

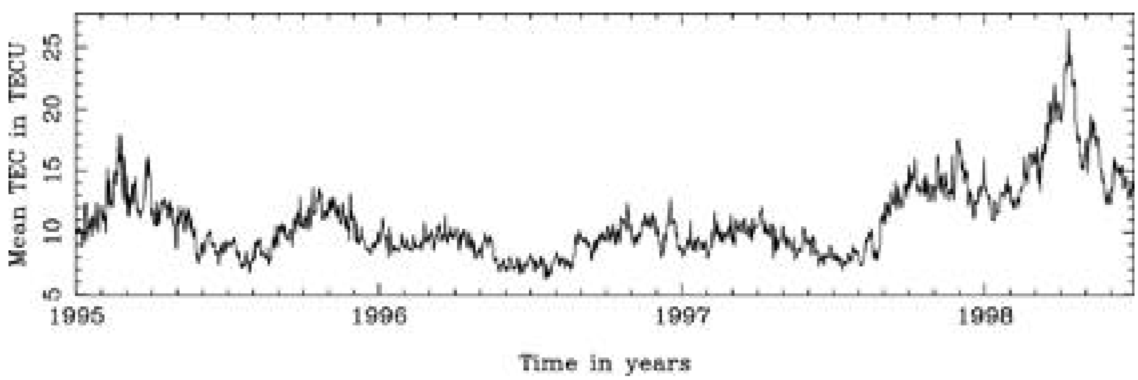

Figure 5. Evolution of the Earth's mean TEC computed by CODE since January 1, 1995

4 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.

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.

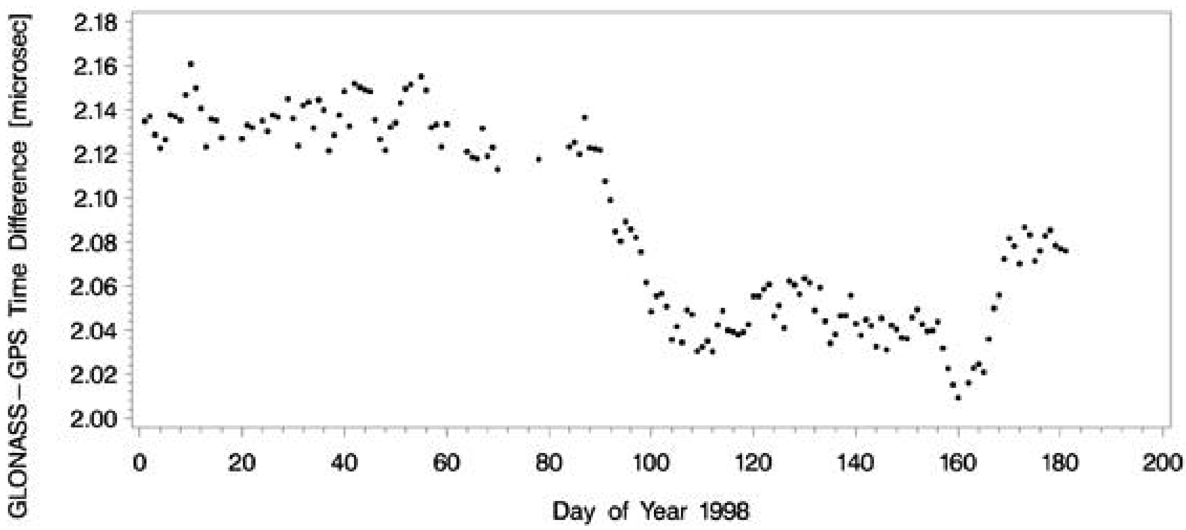

Figure 6. Time difference between the GLONASS and GPS time system.

8 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 parameters. 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.

9 REFERENCES

Feltens, J., and S. Schaer (1998), IGS Products for the Ionosphere, *in Proceedings of the IGS Analysis Center Workshop in Darmstadt, Germany*, February 9-11, 1998.

Le Provost, C., M. L. Genco, F. Lyard, P. Vincent, and P. Canceil (1994), Spectroscopy of the world ocean tides from a finite element hydrodynamic model, *Journal of Geophysical Research, 99*, 24777-24797.

McCarthy, D.D. (1996), IERS Conventions (1996*), IERS Technical Note 21*, Observatoire de Paris, Paris, July 1996.

Niell, A. E. (1993), Global Mapping Functions for the Atmosphere Delay at Radio Wavelengths, *Journal of Geophysical Research, 101* (B2), 3227-3246.

Overney, F., L. Prost, G. Dudle, T. Schildknecht, G. Beutler, J. A. Davis, J. M. Furlong, and P. Hetzel (1998), GPS Time Transfer Using Geodetic Receivers (GeTT): Results on European Baselines, in *Proceedings of the 12th European Frequency and Time Forum EFTF 98*, Warsaw, Poland, March 10-12 1998.

Rothacher, M. (1996), Mean Antenna Phase Offsets and Elevation-Dependent Phase Center Corrections, submitted by e-mail to all Analysis Centers (July, 1).

Rothacher, M. (1998), Recent Contributions of GPS to Earth Rotation and Reference Frames, Habilitation (2nd Ph.D.), University Press, University of Berne.

Rothacher, M., and G. Beutler (1997), The Role of GPS in the Study of Global Change, accepted by *Physics and Chemistry of the Earth*, February 1998.

Rothacher, M., G. Beutler, E. Brockmann, L. Mervart, R. Weber, U. Wild, A. Wiget, H. Seeger, S. Botton, and C. Boucher (1995), Annual Report 1994 of the CODE Processing Center of the IGS, in *IGS 1994 Annual Report*, edited by J.F. Zumberge et al., pp. 139-162, Central Bureau, JPL, Pasadena, Ca.

Rothacher, M., G. Beutler, E. Brockmann, L. Mervart, S. Schaer, T. A. Springer, U. Wild, A. Wiget, H. Seeger, and C. Boucher (1996a), Annual Report 1995 of the CODE Processing Center of the IGS, in *IGS 1995 Annual Report*, edited by J.F. Zumberge et al., pp. 151-174, IGS Central Bureau, Jet Propulsion Laboratory, Pasadena, California U.S.A., September, 1996.

Rothacher, M., W. Gurtner, S. Schaer, R. Weber, and H. O. Hase (1996b), Azimuth- and Elevation-Dependent Phase Center Corrections for Geodetic GPS Antennas Estimated from GPS Calibration Campaigns, in *IAG Symposium No.115,* edited by W. Torge, pp. 335-339, Springer-Verlag.

Rothacher, M., T. A. Springer, S. Schaer, G. Beutler, E. Brockmann, U. Wild, A. Wiget, C. Boucher, S. Botton, and H. Seeger (1997a), Annual Report 1996 of the CODE Processing Center of the IGS, in *IGS 1996 Annual Report,* edited by J.F. Zumberge et al., pp. 201-219, IGS Central Bureau, Jet Propulsion Laboratory, Pasadena, California U.S.A., November 1997.

Rothacher, M., T. A. Springer, S. Schaer, and G. Beutler (1997b), Processing Strategies for Regional GPS Networks, in *Proceedings of the IAG General Assembly in Rio, September, 1997,* Springer, (in press).

Rothacher, M., G. Beutler, T.A. Herring, and R. Weber (1998), Estimation of Nutation Using the Global Positioning System, *JGR,* submitted in March 1998.

Rothacher, M., and L. Mervart (1996*),* *The Bernese GPS Software Version 4.0,* Astronomical Institute, University of Berne, September 1996.

Saastamoinen, I.I. (1973), Contribution to the theory of atmospheric refraction, *Bulletin Géodésique, 107,* 13-34.

Schaer, S., W. Gurtner, and J. Feltens (1998a), IONEX: The IONosphere Map EXchange Format Version 1, February 25, 1998, in *Proceedings of the IGS Analysis Center Workshop in Darmstadt, Germany*, February 9-11, 1998.

Schaer, S., G. Beutler, and M. Rothacher (1998b), Mapping and Predicting the Ionosphere, in *Proceedings of the IGS Analysis Center Workshop in Darmstadt, Germany*, February 9-11, 1998.

Scherneck, H.-G. (1991), A parametrized solid earth tide model and ocean tide loading effects for global geodetic baseline measurements, *Geophys. J. Int., 106*, 677-694.

Schildknecht, T., G. Beutler, W. Gurtner, and M. Rothacher (1990), Towards Subnanosecond GPS Time Transfer using Geodetic Processing Techniques, in *Proceedings of the Fourth European Frequency and Time Forum EFTF 90,* pp. 335-346, Neuchatel, Switzerland.

Springer, T. A., W. Gurtner, M. Rothacher, and S. Schaer (1997), EUREF Activities at the CODE Analysis Center, in *Proceedings of the 4th International*

Seminar on GPS in Central Europe, Vol. 4(27), pp. 165-176, Warsaw University of Technology, Warsaw, Poland, May 7-9, 1997.

Springer, T. A., G. Beutler, and M. Rothacher (1998a), Improving the Orbit Estimates of the GPS Satellites, *Journal of Geodesy*, submitted January 1998.

Springer, T.A., G. Beutler, and M. Rothacher (1998b), A new Solar Radiation Pressure Model for the GPS Satellites, in *Proceedings of the IGS Analysis Center Workshop*, edited by J.Dow et al., ESA, Darmstadt, Germany, February 1998.

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The ESA/ESOC IGS Analysis Centre

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1 Introduction

In 1997 we have continued our contribution to the IGS that was initiated in 1992. We have incremented the number of products to accomplish the last IGS requirements and recommendations.

This year has been characterized by the following:

- The production of predicted orbits has been developed and initiated. We contribute regularly to the IGS predicted orbit since April 1997.
- The quality of our products has been improved by the estimation of empirical accelerations and the implementation of new tropospheric and ocean loading models.
- Further developments have been carried out in the Ionospheric Monitoring facility in preparation to the regular production of combinations and the creation of a new IGS product in 1998.
- In the field of satellites carrying GPS receivers, the TOPEX/Poseidon analysis activities, performed more than two years ago, have been resumed with the Automated Rendezvous Pre-development (ARP). The analysis of the first Flight Demonstration took place in 1997. Several of our routine IGS products have been used for the data analysis.

2 ESOC GPS Web Pages

Additional information on GPS related activities at ESOC can be found at our web pages:

html://nng.esoc.esa.de

3 ESOC IGS Analysis

An updated description of models and parameters used in our routine processing is located at:

http://igscb.jpl.nasa.gov/igscb/center/analysis/esa.acn

4 Computer Resources and Software Description

The software has been integrated in the last years under the GPS Tracking and Data Analysis Facility (GPS-TDAF). It is a UNIX based environment for which main tools have been developed in FORTRAN for the numerical computations and in tcl/tk for the scripts that control the automatic processing and for the graphical user interfaces.

The GPS TDAF is made up of three main tools:

- The Remote Station monitor and control. It retrieves, preprocesses and distributes the data of the ESA GPS receivers Network.
- The External Sites monitor and control. It retrieves the RINEX data that are used for the processing of our IGS products.
- The IGS processing monitor and control. It allows the operations related to of the final, rapid and predicted products.

A special emphasis has been put on the system automation, and it has proven to be robust for periods of several days with a very sparse remote operator control. The main problems arise from the computer loading at ESOC, the huge amount of involved data and the sequential nature of the products, that depend on the success of the processing of the previous days.

5 Data Archiving

A 7 Gigabytes disk is accessible to the workstations through the ESOC network. There is space for the computation of two or three weeks and then products and data are archived in a robot tape system. Old data can be put on line for reprocessing.

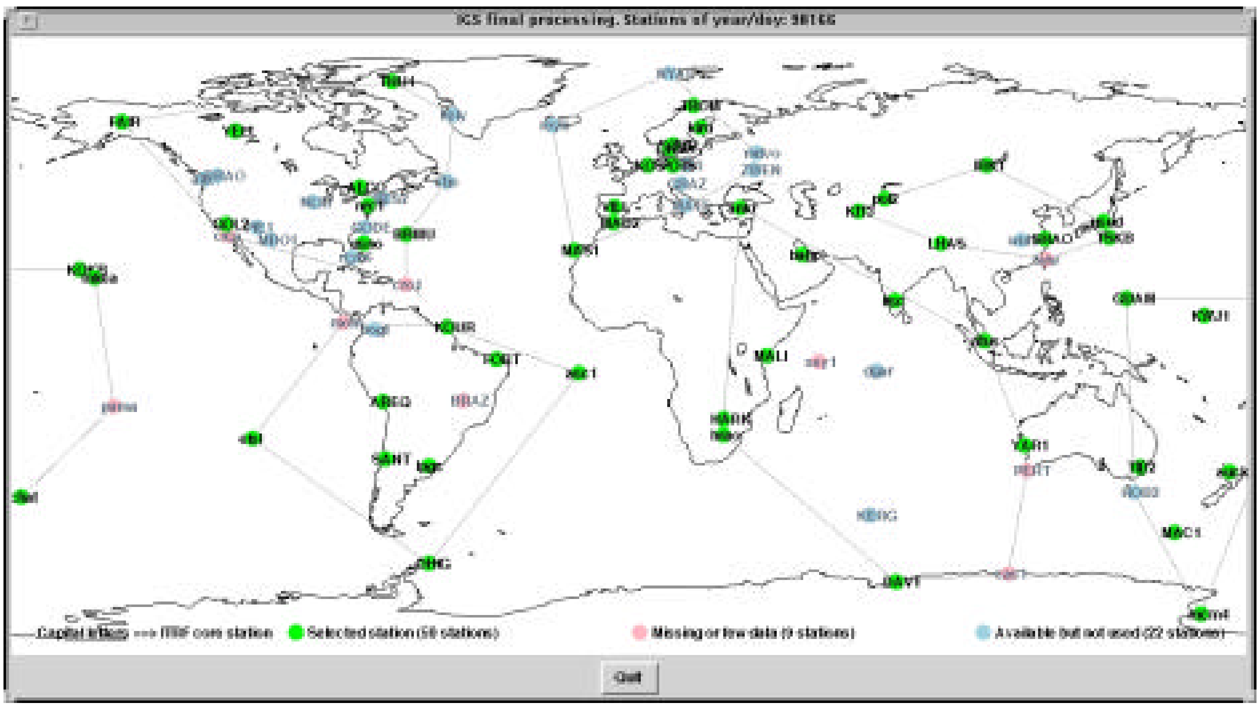
6 ESOC IGS Analysis Centre Major Routine Analysis Changes in 1997

31/03/97	Estimation of sine and cosine radial empirical acceleration instead of impulses every 12 hours
09/03/97	Saastamoinen tropospheric model replaced the Willman one
02/04/97	ESA predicted orbits available

21/04/97	Deadline of rapid orbits reduced from 23:00 to 21:00 UTC
22/07/97	Hatanaka compression implemented for the analysis and for the data distribution of the ESA receivers
30/11/97	Ocean loading implemented based on the Scherneck model

7 Tracking Network

The following panel is part of the GPS Tracking and Data Analysis Facility and shows for a given day the stations that are considered in the processing.



8 Predicted Orbits

Earth fixed positions taken from the rapid IGS solution are used as basic observable. The number of days for the fit is variable, currently set to four. If the IGR rapid orbit is not accessible our corresponding rapid solution plus eop's are used instead. Measurements of the last day have a weight three times the one of the initial days.

Per satellite are estimated ROCK4T scale factor, ybias and sine and cosine one cycle per revolution empirical accelerations in the three orbital directions. The initial state vector is taken from the corresponding rapid solution. It is also estimated.

Earth orientation parameters are taken from the rapid solution for the fit interval and from the IERS rapid service for the prediction. xp, yp and ut1 in the prediction interval are corrected for the offset with respect to the IGS rapid eop's.

Satellites are deweighted if

- they have been deweighted in the rapid solution
- are missing any of the days of the rapid combination
- are in eclipse period
- the orbit determination fit of the 4 igr orbits is poor.

Satellites with a extremely bad fit in the 4 day igr interval are replaced by the propagation of our last rapid solution. It has been proven that a propagation of a smaller arc is better.

9 Rapid and Final Orbits

Rapid and final orbits are mainly differentiated by the amount of data available. Rapid orbits are initiated at 14:00 UTC after collection of all the available data. The data arc is 12+24 hours and the processing time about 4 hours. Final orbits are initiated with a delay of several days for data collection. The data arc is 12+24+12 hours and the processing time about 12 hours in a SUN Sparc 20.

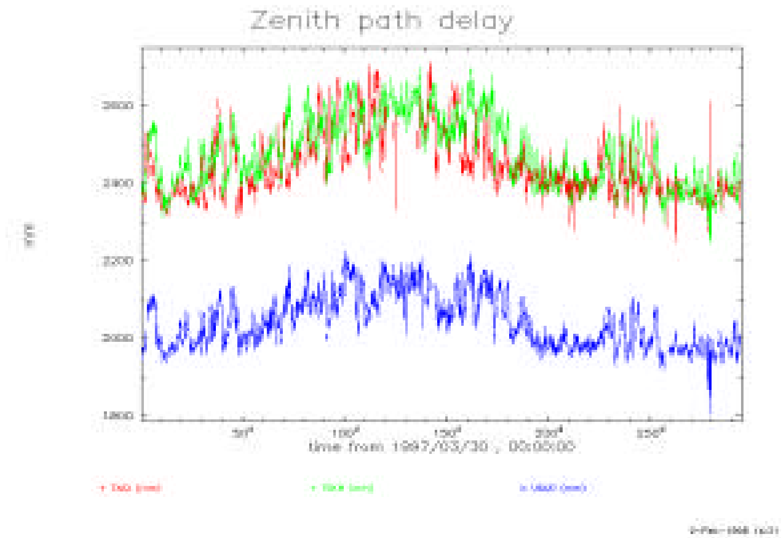
The orbit modelling is common. Per satellite we estimate the following parameters:

- Position and velocity at epoch.
- Scale for ROCK4T, y-bias, sine and cosine radial component one cycle per revolution empirical accelerations. These parameters replaced the delta-v impulses every 12 hours for all the satellites in March 1997.
- For eclipsing satellites the observations are excluded half an hour before and after the eclipse. Delta-v are estimated in the three orbital components at eclipse exit time.
- Any delta-v due to spacecraft manoeuvres.

10 Tropospheric Estimates

Tropospheric zenith path delays are produced in our routine analysis. They are estimated along with orbits, eop's and station coordinates. We use the Saastamoinen model since March 1997. The model consists of two hourly step functions with apriori values taken from the previous day.

In the following example the results for three stations, USUD, TSKB and TAEJ from the same region are presented. The three curves show the same seasonal variation. Taejon and Tsukuba are located close to the sea level while Usuda is at about 1500 meters height. That explains the difference of about 400 mm between the curves. The geographical proximity between Usuda and Tsukuba makes both profiles to look very similar in spite of the height difference.



11 Ionosphere Processing

At the beginning of 1998 the routine processing of ionosphere TEC maps and satellite/receiver differential code biases (DCBs) in final and in rapid mode has been started at ESOC. The first day that was processed in final mode was the 28 December 1997, and processing in rapid mode started for 19 March 1998. 24 hours of so called TEC observables, derived from carrier phase leveled to code data, are fitted to 2-d single layer TEC models, as well as to Chapman profile models to resolve the ionosphere's electron content 3-dimensionally. The processing sequence is as follows:

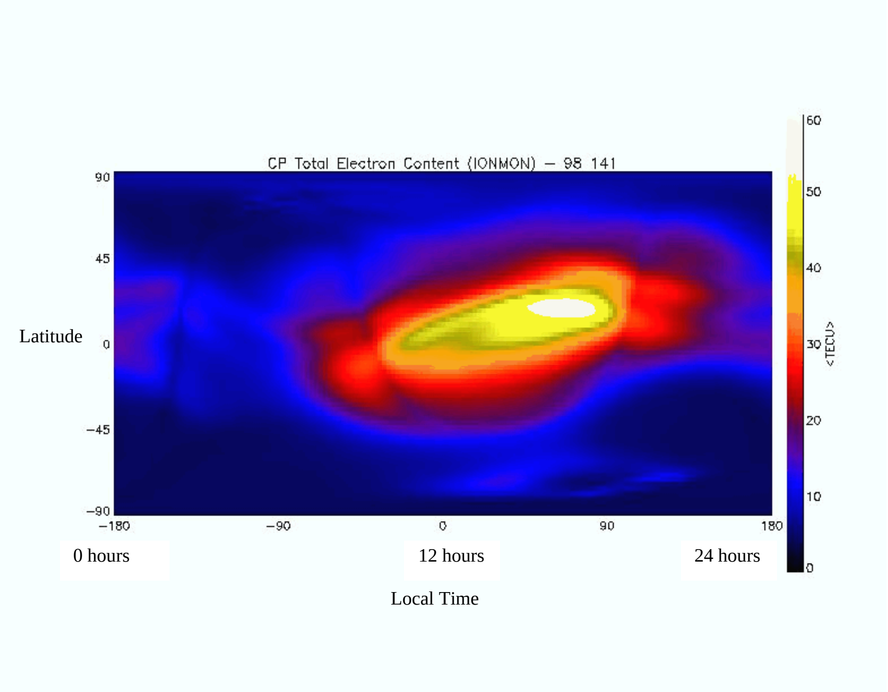
1) A nighttime TEC data fit is made to obtain reference values for the DCBs. The nighttime TEC itself is absorbed in this fit with a low degree and order spherical harmonic. In the other fits 2) - 4) these DCBs are then introduced as constraints.

2) A Single layer Gauss-Type Exponential (GE) function is fitted to the TEC data. The results of this estimate are intended for the ESOC-internal interpretation of results and comparison with the other fits.

3) A Chapman profile model is fitted to the TEC data, where the layer of maximum electron density N0 and its height h0 are estimated as functions of geomagnetic latitude and local time. h0 is restricted to achieve values within a predefined height range only, currently 400 km =< h0 =< 450 km.

4) A Chapman profile model is fitted to the TEC data, where now h0 is fitted as a global constant.

Since the beginning of June 1998 ESOC is contributing to the IGS Ionosphere Working Group's pilot phase. Fit no 3) in final mode is currently delivered to the IGS Ionosphere pilot project. The figure below shows a TEC map from a fit of type 3).



12 Manoeuvres Estimation

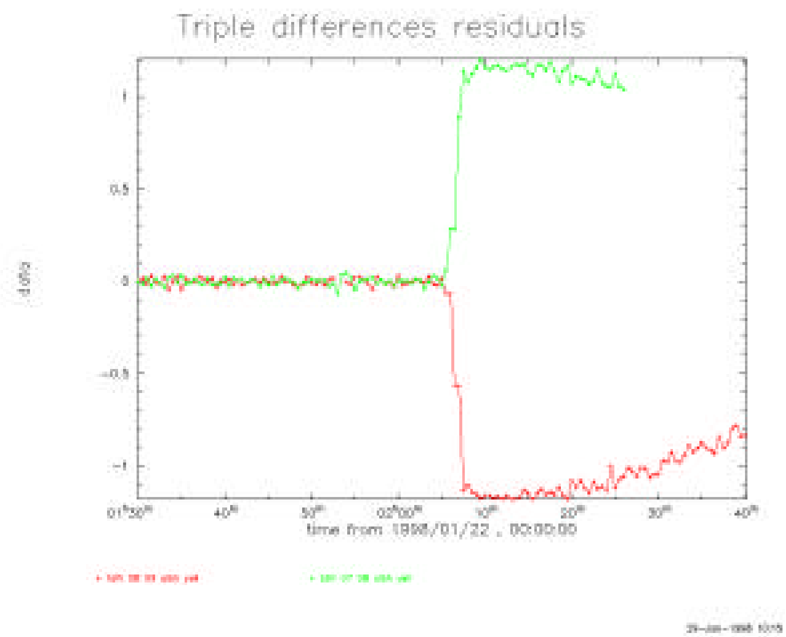
For the estimation, the manoeuvres must be previously announced in the NANU's. If at least two receivers track the manoeuvring satellite we try to detect the time when the thrusters are fired using two alternative ways:

- Studying the residuals of the phase triple differences for combinations that include the satellite. The time is determined by looking for a step in the triple differences caused by the new range rates produced by the change in velocity. The preliminary value of along track delta-v is estimated by the energy change. See plot below.

- Using clock bias free ionospheric free carrier phase time differences. We have developed an algorithm to detect delta-v changes based on the comparison of the observations to a propagated orbit. We obtain directly the estimate of delta-v.

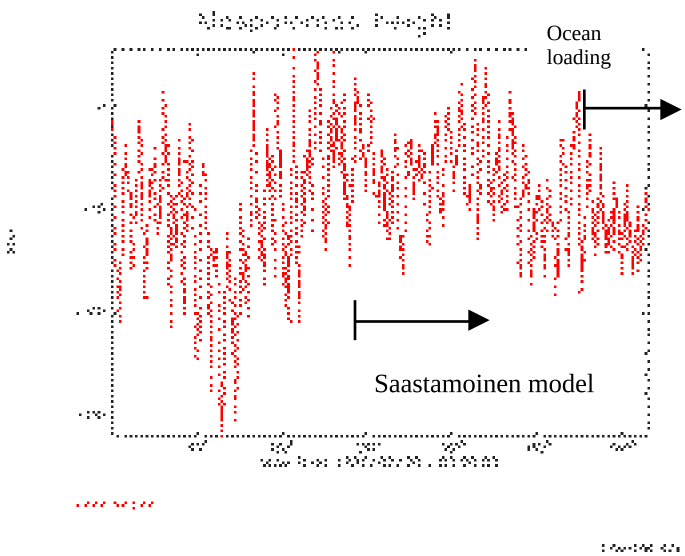
Once the manoeuvre time is known and with a initial estimate of delta-v, our orbit determination program BAHN estimates the orbit and impulse in three directions. Radial and cross track components are normally negligible compared to the along track component. Observations one hour before and after the manoeuvre are not considered because of difficulties with the fit.

We have estimated all manoeuvres since the beginning of IGS. Only in a very few cases did the lack of visibility not allow us to detect the firing time. The current network densification facilitates the detection.



13 Station Coordinates

The stability of the station coordinates has been improved -specially the vertical component- with the implementation of the Saastamoinen tropospheric model in March 1997 and also with the consideration of ocean loading based on the Scherneck model. That can be clearly seen below on the height estimation of Maspalomas, a station very affected by the ocean loading effect. Several tidal effects, specially the monthly one, have been substantially reduced.



14 Products

Our routine products are the following:

- Final orbits esawwwwd.eph, being wwww the gps week and d the day of the week (0-6), distributed via CDDIS. 11 days delay.
- Rapid orbits esawwwwd.eph, being wwww the gps week and d the day of the week (0-6), distributed via EMR. 21 hours delay since April 1997Predicted orbits espwwwwd.eph, distributed via EMR.
- daily rapid eop (pole, LODR) solutions in IERS format: esawwwwd.erp.
- weekly final eop (pole, LODR) solutions in IERS format: esawwww7.erp.
- weekly summaries: esawwww7.sum.
- weekly free network station coordinate solution in the SINEX format: esawwww7.snx
- daily tropospheric files containing Zenith Path Delay estimations esawwwwd.tro

15 References

J. M. Dow, T. J. Martin Mur, and M. M. Romay Merino, ESA's Precise Orbit Determination Facility, ESA Bulletin no. 78, May 1994, pp. 4O-50.

H. Fliegel, T. Gallini, and E. Swift, Global Positioning System radiation force model for geodetic applications, J. Geophys. Res. 97(B1), pp. 559-568, January 1992.

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

D. D. McCarthy (ed.), IERS Conventions (1996), IERS Technical Note 21, Observatoire de Paris, July 1996.

J. T. Wu, S.C. Wu, G.A. Hajj, W.I. Bertiger, and S.M. Lichten, Effects of antenna orientation on GPS carrier phase, Manuscripta Geodaetica (1993) 18, pp. 91-98.

Sinex Working Group. SINEX - Solution (Software/technique) INdependent EXchange Format. Version 1.00 (April 01, 1996).

T.J.M. Mur, J.M. Dow, C.G. Martinez, J. Feltens. The ESA/ESOC IGS Analysis Centre. 1996 IGS Annual Report.

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GFZ Analysis Center of the IGS - Annual Report 1997

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1 Introduction

In the last year, a further improvement of accuracy and quality of the products has been gained. The rapid and final orbits reached the 6 cm and 4 cm level, respectively, and the polar motion crossed the 0.1 mas "boundary."

The software and the technology were changed to get the various products compatible to the final orbits. The clock solution was aligned to the GPS time frame.

The zenith path delay (ZPD) products from all the ACs are combined at GFZ to an official IGS product (see Gendt, this volume).

2 Routine IGS Processing - Overview

The technology for the generation of rapid and final products was already described in the last annual report. During 1997, changes were made to be more effective and to get compatible final products (see Table 1). An overview of both GFZ products, and all daily and weekly activities, is given in Table 2.

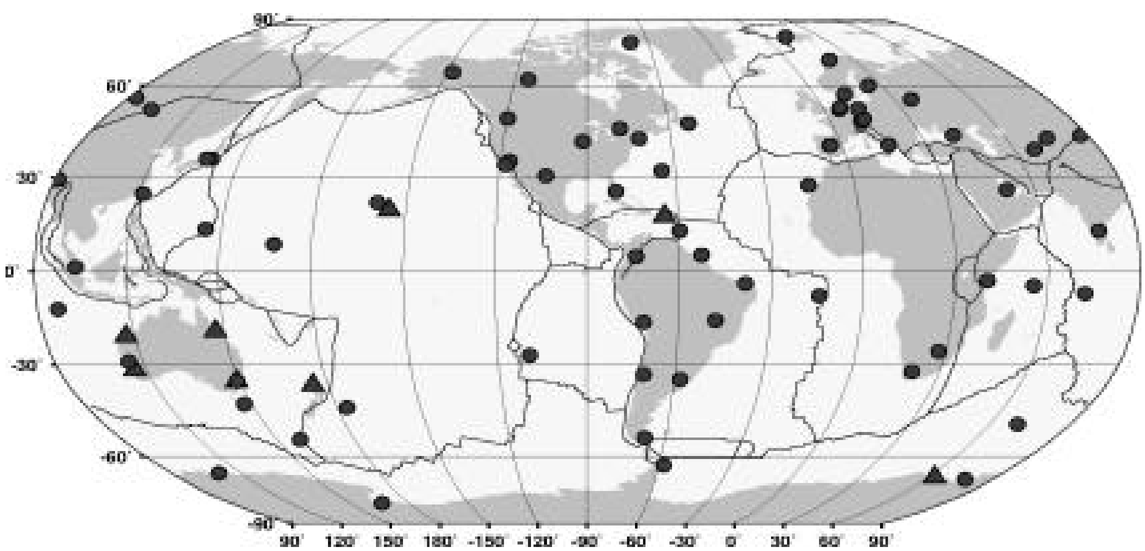

Fig. 1. Global distribution of stations used in the IGS analysis of GFZ
(✿ - sites added for rapid analysis)

Table 1. Modification in software and technology

Week	Date	Description
902	1997-04-20	Use of an optimized set of ~30 sites for rapid analysis
903	1997-04-27	ERP from 3-day arcs (middle day), UT is solved for
921	1997-08-31	Calibration of clock products (alignment to GPS time frame)
929	1997-10-26	Introduction of Niell mapping function
939	1998-01-04	Compatible clocks (use of 3-day orbits for clocks)
944	1998-02-08	5-min sampling rate, 15 degree elevation cutoff angle
945	1998-02-15	Introduction of tropospheric gradients
947	1998-03-01	Introduction of ITRF-96 with 47 core sites
949	1998-03-15	SINEX using 3-day orbits (compatible to SP3 orbits)
951	1998-03-28	Error for PRN8 corrected (IIR to IIA)
958	1998-05-17	PRN13: antenna phase center offset changed from 1.6746 m to 1.0229 m

Since March 1998, the raw RINEX data are handled in the Hatanaka format. All input files not submitted in this format are converted into this format just after ftp prior to analysis.

Starting with GPS week 944, we switched from 20 degree elevation cutoff to 15 degrees. At the same time, the sampling rate was reduced from 6 to 5 minutes, so that we could get exact satellite clock estimates for all 15-minute epochs in the sp3 product.

It should be mentioned that for PRN8 (started in November 1997), a wrong block number (IIR instead of IIA) was erroneously introduced. After correction in March 1998, our overall orbit quality improved by 1 cm (Figure 3). This demonstrates that at the level of 5 cm, such an incorrect parameter influences the orbit solutions for all other satellites.

2.1 Rapid Analysis

A set of 20-30 well-distributed sites is sufficient to get high-quality satellite orbits. Starting with GPS week 902, an optimized set of ~30 sites was selected, resulting in reduced computation time for the total rapid analysis (about 2-3 hours). To have a long history, we tack on a selected set of sites in our final analysis. However, occasionally these sites do not come in a timely manner, so for the rapid analysis, some additional sites were selected.

2.2 Final Analysis

The data cleaning part was changed to use the precise point positioning (PPP) technique based on the satellite clocks from the rapid analysis. This cleaning is more effective and more flexible than the formerly-used double difference procedure, which is now used only for the rapid analysis.

The strategy for deriving the final products was changed to get products that are compatible to each other. The old products for ERP and SINEX were based on daily orbits, whereas the sp3 product was formed using 3-day arcs.

The new technology is the following:

Table 2. Overview of IGS routine analysis and generated product (D denotes actual day)

1-day orbits	
■ Rapid analysis for D-1 (start 9:00 UT)	*gfzwwwwd.erp*
· Optimized set of ~30 sites *gfzwwwwd.sp3p*	
· DD-Clean	*including sat-clocks*
· Analysis and post-fit-cleaning (iteratively)	*(12:00 UT)*
■ Predictions	*gfpwwwwd.erp*
· IGR products for D-4 to D-2 and GFZ rapid products for D-1 used	
■ Final analysis	
· PPP-cleaning using rapid clocks	
Final Solution, weekly	
■ 3-day orbits by combining NEQ of 1-day orbits	*gfzwwwwd.sp3*
· Output of NEQ implicitly containing the 3-day orbits (not fixed !)	
■ ERP are taken from the middle day of the 3-day orbit solutions	*gfzwwwwd.erp*
■ Weekly SINEX is computed by stacking the above NEQ for 7 days (data of each day are used in three NEQs)	*gfzwwwwd.snx*
■ To get compatible products clocks and (real-valued) ambiguities are computed fixing the above sp3 orbits	*sat-clocks*
■ ZPD solutions with a higher sampling rate are effectively computed by fixing the above ambiguities	*gfzwwww.tro*

All products are based on fixing the station coordinates of the core sites (since March 1998 47 sites of ITRF96, before that 13 sites of ITRF94). The sp3 orbits are computed using 3-day arcs (by stacking NEQs of 1-day arcs). Simultaneously with the orbit product, a 3-day NEQ is formed containing only the station coordinates and ERPs, but also implicitly including the 3-day orbits (Helmert blocking; orbits are not fixed!).

For each 3-day arc daily ERPs are computed with continuation constraints for the day boundaries (i.e., polar motion and trend as well as UT and LOD form a continuous polygon). The solution for the middle day of each arc is the official product. Each week, a UT series is compiled by concatenation of the daily values and starting at Bulletin A value.

Because the sp3 orbits are computed by stacking NEQ there are no simultaneously solved clocks. Therefore an additional step was introduced at which all clocks and (real valued) ambiguities are determined by fixing the given orbits. These products are now consistent to the best orbits. Such clocks can be used in the well-known precise point positioning. For the derivation of the ZPD product with hourly sampling rate (in the routine analysis 4 hours are used), the derived ambiguities are introduced and fixed. This way the new analysis can be done within minutes. I n addition, the ZPD values are adjusted using the adjacent days (3 days in total) to smooth the solution at the day boundaries.

3 Improvement of the Clock Solution

Before GPS week 921, the GFZ clock solutions (rapid as well as final) showed significant offsets and drifts compared to the IGS combined solutions. The differences in the offset reached values up to 1 microsecond and the trend difference was normally in the range of 80-90 nanoseconds per day. T o overcome the problem of singularity within the estimation process, the satellite and station clocks are reduced to a specified reference clock. Usually as a reference, one of the station clocks is taken which is known to be very stable. At GFZ, the station clock of Algonquin is used as reference most of the time. Before GPS week 921, the satellite clocks taken directly from the adjustment were delivered as the final results. However, the connection to a specified reference clock led to differences compared to GPS time because of the behavior of the reference clock. It is only stable with the exception of a small rest, and therefore includes a time-varying offset and drift. Beginning with GPS week 921, the GFZ clock solution was corrected for these effects. In a first step, possible resets or jumps of the reference clock which appear sometimes are detected and corrected by comparing the reference clock with other stable station clocks. Missing epochs of the reference clock, which normally led to gaps in the final clock solution, can now be bridged over. The offset correction is then performed by calculating an average over all satellites. The drift correction is estimated by the trend over all mean values.

Figure 2 shows the improvement of the final clocks of GFZ for both offset and trend as a result of the changes. Before week 921 the drift was nearly constant in the range of 90 nanoseconds per day (reflecting the clock characteristic of Algonquin) whereas after the software improvement it was usually a few nanoseconds.

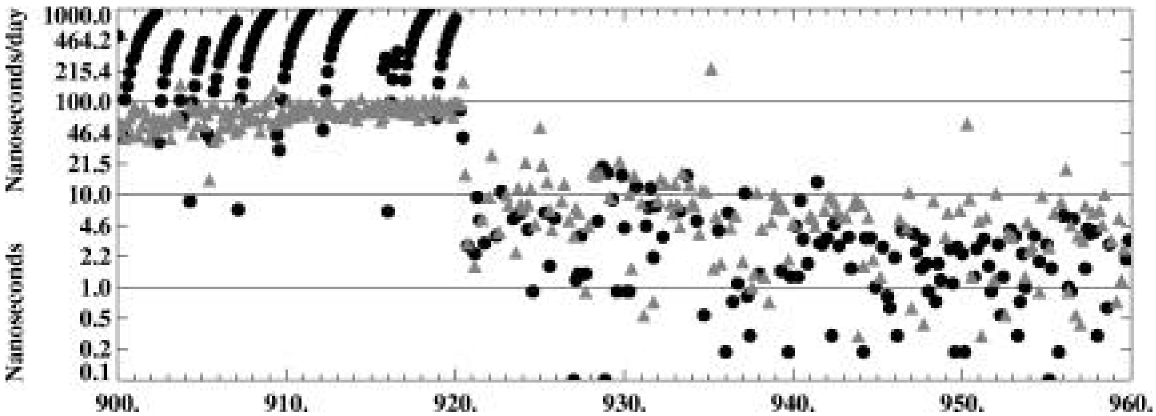

Fig. 2. Offset (✿, [ns]) and trend (✿, [ns/d]) of GFZ satellite clock results as compared to the GPS time frame

It should be mentioned that there are some inconsistencies between the ACs concerning the antenna phase center offset for PRN13 which results in higher clock differences. When GFZ switched from 1.6764 m to 1.0229 m, the value used by most ACs, the level of our clock differences improved to 0.2 ns (Figure 3).

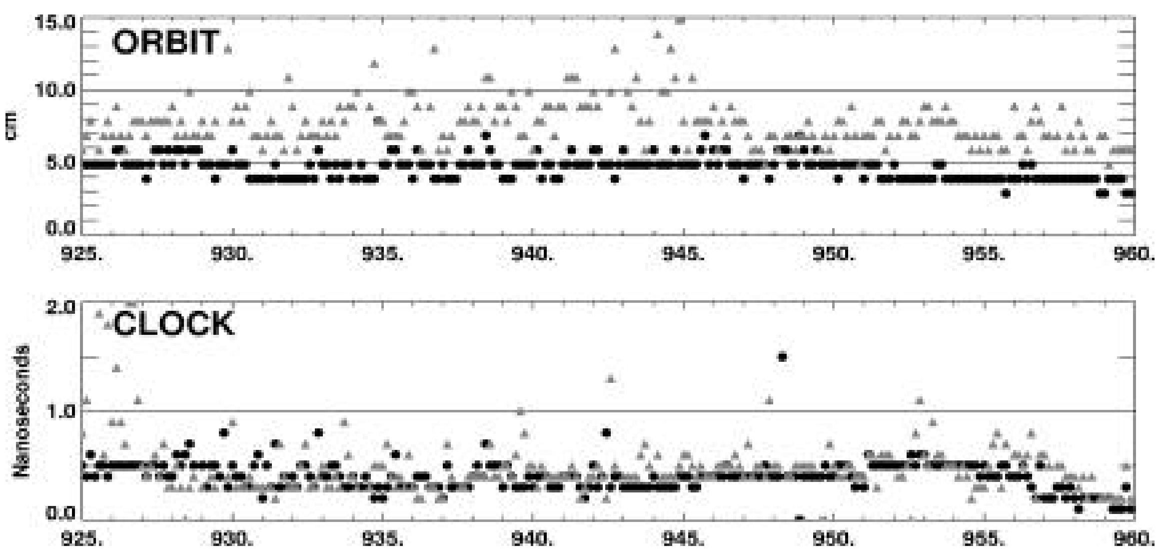

Fig. 3. Daily median of GFZ final (✿) and rapid (✿) orbits compared to the official IGS Product

4 High Rate Satellite Clocks

Based on the results of the IGS final analysis which is usually done with sampled data, the computation of high-rate satellite clocks (i.e., with the original data rate) can be carried out with a small additional amount of computation time.

After the IGS final processing, precise GPS satellite orbits are available which can be introduced as fixed parameters. On the other hand, all ambiguities within the sampled data are estimated within the IGS adjustment, and all bad data and outliers are identified. With this information, the raw 30-sec RINEX data files are reduced to those parts for which the ambiguities are valid. New data before or after are neglected. As a result of such pre-processing, new ambiguities may not be found within the high rate data. Beyond this, the GPS data between the low rate epochs are separately inspected for bad records. A selection of about 20 stations seems to be sufficient for a good global coverage. Because this number of stations in general is smaller than the number of stations used in the IGS final analysis, the starting time of the ambiguities is not identical with the starting time of the original scene. Therefore, the ambiguities have to be shifted to the correct new epochs to avoid the problem that new ambiguities are automatically found by the program.

At this moment the precise high-rate clocks are not estimated routinely but a periodical and automatic computation can be installed easily. More details and results can be found in (Söhne, 1998).

5 Products

5.1 Orbits

The quality of the orbit solutions was 5-6 cm for the final and 6-10 cm for the rapid variant. The introduction of the ITRF96 with the 47 core sites to be held fixed (week 947), stabilized the realization of the reference frame and led to an improvement for the orbits, especially for the rapid solution. The orbits are now on the 4 cm level for the finals and on many days on the 6-7 cm level for the rapids (Figure 3).

5.2 Earth Rotation Parameters

The accuracy for the ERP determination was already on a high level (see Table 3) and could even be improved during the past year. By using 3-day arcs for the determination of ERP (starting in week 904), the LOD solution improved significantly (Figure 4). A further improvement was reached in March 1998 by the introduction of the enlarged set of core sites which stabilized the reference frame realization during the daily analysis. The largest effect can be seen for the rapid products (Table 3, Figure 4), which have now an accuracy of 0.15 mas, and corresponds to the former accuracy of the final product. The improvement in the rates is not as dramatic. Since week 903, GFZ also submits UT results which are aligned to Bulletin A on the first day of each week. The accuracy within the week is at 0.07 ms.

Table 3. Accuracy of ERP determination for Rapid and Final Products

	Rapid*		Final	
	ITRF94	ITRF96	ITRF94	ITRF96
xp	±0.29	±0.16	±0.11	±0.07
yp	±0.29	±0.14	±0.15	±0.09
LOD	±0.36	±0.31	±0.26	±0.16

* outliers removed

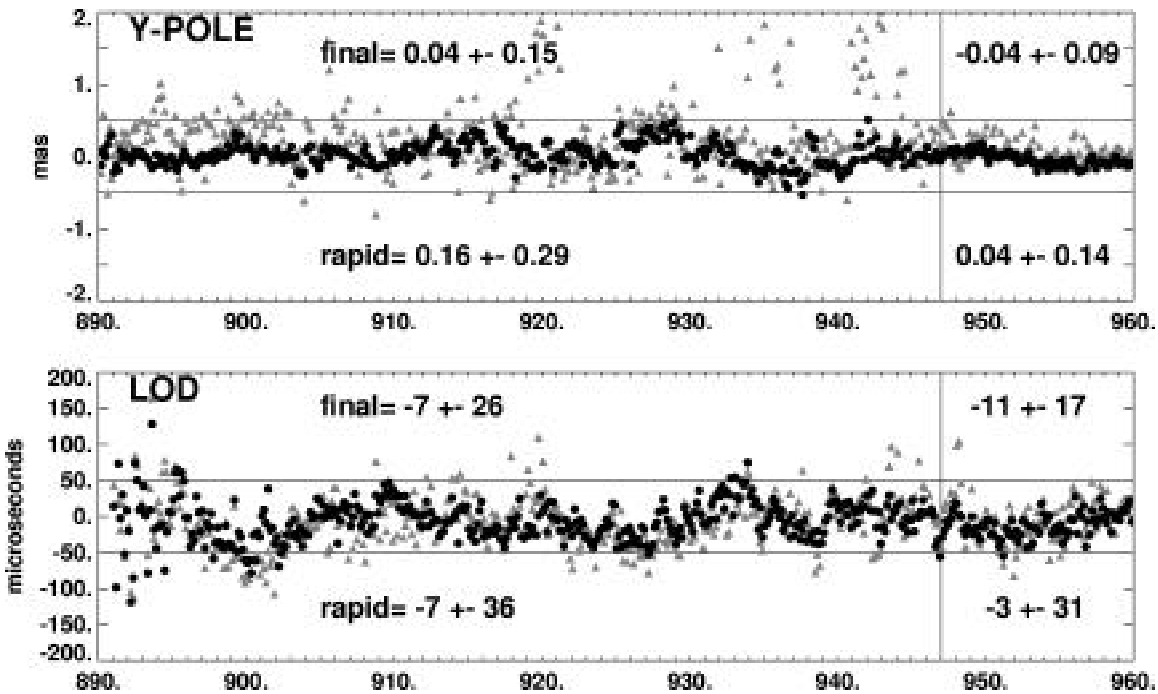

Fig. 4. Differences of GFZ final (✿) and rapid (✿) ERP solutions to the IGS final results.

5.3 Global Reference Frame and Plate Kinematics

To continue our investigations of recent global tectonics and for the determination of a global reference frame, one more year of IGS data was added to our analysis. The solution for the reference frame was computed according to the description in previous reports (Gendt et al., 1997). Site velocities were adjusted for all sites which were analyzed for more than one year (65 sites). The velocity in height was loosely constrained. The orientation of the system was defined by applying no-net-rotation constraints both for the site coordinates and the site velocities, as a reference the ITRF96 reference frame including velocities was used.

The quality of the determined reference frame is on the sub-cm level. Helmert transformation to ITRF96 gives residuals in north, east and up of 1.9 mm, 7.1 mm, 5.6

mm, respectively (for the 47 core sites). Larger discrepancies in the east component were observed for SANT, AREQ and KWJ1. For the dense parts of the network in Europe and North America (28 sites), the residuals are 1.2 mm, 2.8 mm, 3.2 mm. The global residuals to ITRF96 for the site velocities are in the range of 2-3 mm/y for all three components (2 mm/y in Europe and North America). Again some sites were excluded due to large discrepancies in the velocities, e.g., SANT, AREQ, MALI, OHIG.

Figure 5 presents the station velocities from our global solution over 5 years. The corresponding values from ITRF96, so far as available, are shown for comparison. A considerable improvement can be noted for the Australian sites (e.g., YAR1, HOB2, TIDB), as well as for the sites of East Asia and Japan (TAIW, USUD, TSKB), which showed rather large discrepancies in the past. Also a number of relatively new sites like GUAM, KERG, KWJ1, CAS1 and DAV1 are in better agreement now, so that in general a better quality both of ITRF and GFZ solution can be stated. The most remarkable region with large discrepancies remains South America, where further investigations and checks of the solution quality are obviously needed.

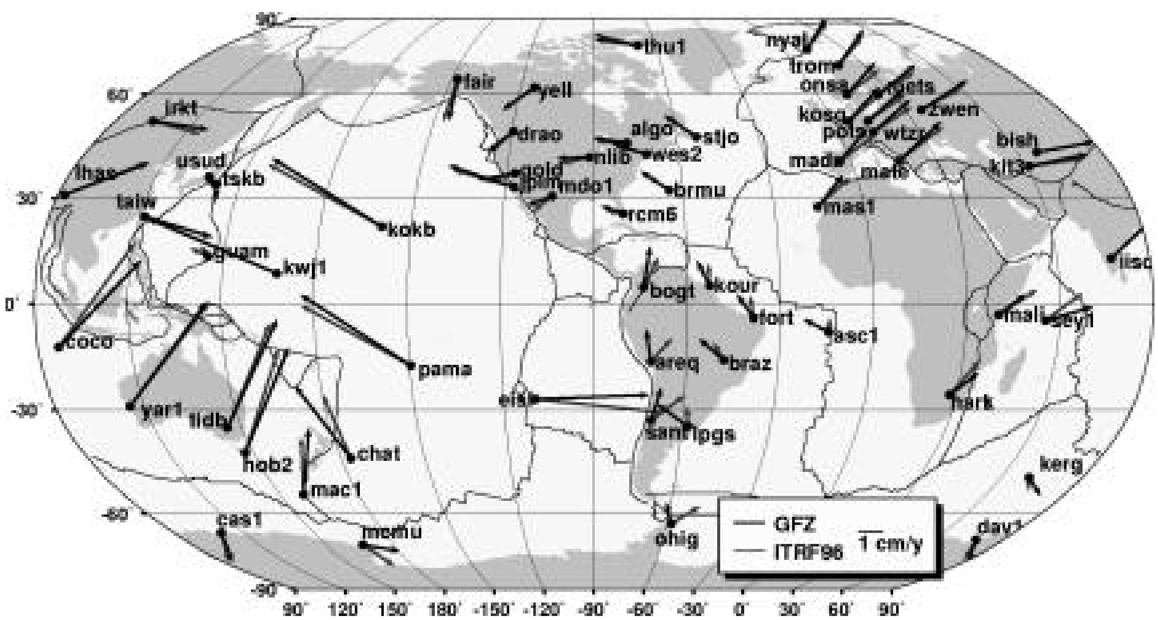

Fig. 5. Site velocities from GFZ solution from 5 year IGS data together with ITRF96 values

Figure 6 demonstrates a significant improvement of the GFZ coordinate solution achieved after the introducing of ITRF96 at week 947. Here, differences in 3 components between the GFZ coordinate solutions and the combined JPL GNAAC solutions are given.

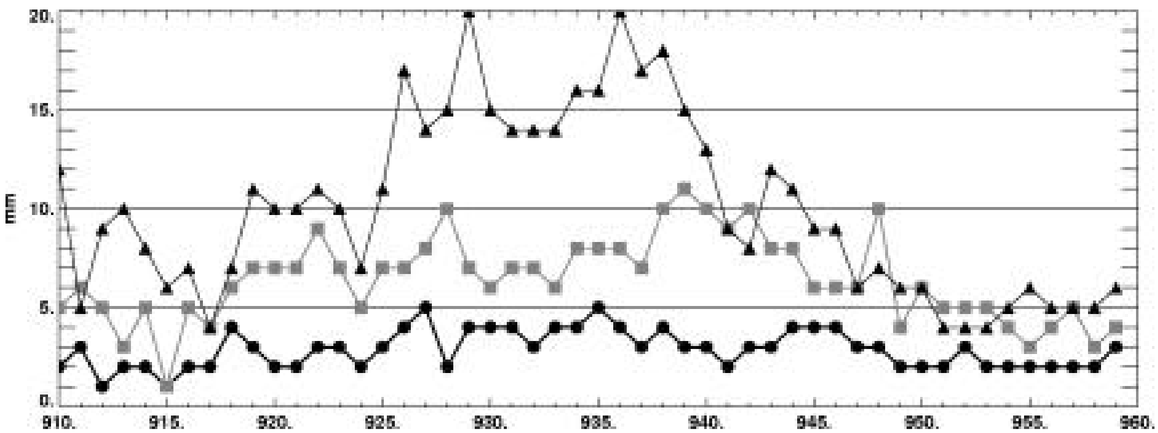

Fig. 6. Differences between GFZ coordinate solution and the combined solution of JPL GNAAC in north (✿) , east (✿) and height (✿).

5.4 Troposphere

The quality of the zenith path delay solution is on the level of 3-4 mm (More details see Gendt, 1998).

6 References

Gendt, G., G. Dick and W. Söhne (1997): GFZ Analysis Center of IGS - Annual Report 1996, *International GPS Service for Geodynamics, 1996 Annual Report, ed. by J.F. Zumberge, D. E. Fulton and R. E. Neilan, JPL, California*, pp. 169-181

Gendt, G. (1998): IGS Combination of Tropospheric Estimates - Experience from Pilot Experiment, in *Proceedings of the IGS Analysis Center Workshop, Darmstadt, February 9-11, 1998*, in press

Söhne, W. (1998): Precise high-rate satellite clocks at GFZ, in *Proceedings IGS Analysis Center Workshop, Darmstadt, February 9-11, 1998*, in press

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JPL IGS Analysis Center Report, 1997

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1 Summary

JPL activities as an IGS Analysis Center continued throughout 199. Regular deliveries of rapid (1-day), precise, and high-rate (30-sec) GPS orbits and clocks, Earth orientation parameters, and free-network ground station coordinates (now in SINEX 1.0) were maintained. A new product was made available in 1997 - daily troposphere estimates in the IGS exchange format. The estimation of tropospheric gradients has further improved the accuracy of our solutions. In early 1998, a larger subset of the newly-augmented group of 47 IGS fiducial stations was put in use, and all fixed-network solutions were made to align with ITRF96. Shortly thereafter, only free-network products rotationally aligned with ITRF96 are submitted.

2 Evolution in 1997

Material relating to JPL (Jet Propulsion Laboratory) participation as an IGS analysis center, beginning in 1992, can be found in [1] and references therein. [2] describes JPL activities as a GNAAC (Global Network Associate Analysis Center).

Table 1 indicates the evolution of our activities during 1997. A major event was the estimation of tropospheric gradients (see section 5 of this document). Also, JPL station coordinate solutions now conform to the SINEX 1.0 format. We thank Remi Ferland of NRCan for providing the SINEX conversion utilities and assisting in their implementation at JPL.

Table 1: Analysis evolution, 1997 through early 1998

Action	Date
Produce troposphere files in IGS Exchange format	Jan 26
Produce station coordinate files in with SINEX 1.0 format	Jan 26
Produce free-network transformation files routinely	Apr 15
Do not process satellites deleted from rapid-service product	Apr 23
Estimate tropospheric gradients	Aug 24
Use TurboRogue MAD2 (in place of MADR) as a fiducial site	Nov 9
Correct mismodeling of SRP for PRN03	Nov 9
Use NRC1 (instead of ALGO) as default reference clock	Dec 14

Use 32-hour nominal orbit interval, map final orbits for 30 hours	Feb 1, 1998
Use ITRF96 coordinates and velocities for 22+ subset of 47 IGS fiducials	Mar 1
Use free-network estimates in troposphere products	Mar 15
Lower threshold of global site RMS isolation from 2000 to 1800 km	Mar 18
Use USNO (instead of NRC1) as default reference clock	Apr 26
Increase a priori sigma for pole rates from 0.18 to 0.50 mas/day	May 6
Use all free-network solutions for products and AC summary report stati:	Jun 28

3 Product Summary

Tables 2 and 3 summarize the regular products that result from JPL IGS AC activities. New products are the daily, site-specific troposphere estimates in IGS Exchange format. These are described in Section 5 of this report. Table 4 indicates addresses of World Wide Web pages with related information.

Table 2: Regular products from the JPL IGS Analysis Center, at ftp://sideshow.jpl.nasa.gov/pub/jpligsac

Example File	Contents
0937/jpl0937.sum.Z	narrative summary for GPS week 0937
0937/jpl0937[0-6].sp3.Z	precise orbits for days 0-6 (Sun through Sat) of GPS week 937
0937/jpl0937[0-6].yaw.Z	yaw-rate data for eclipsing satellites, days 0-6, GPS week 937
0937/jpl09377.erp.Z	fixed-network Earth orientation parameters for GPS week 937 (free-network beginning week 964)
0937/jpl09377.snx.Z	free-network station coordinates for GPS week 937 (7-parameter transformation to ITRF beginning wk 947) (3-parameter rotation to ITRF beginning wk 964)
0937/jpl0937[0-6].tro.Z	fixed-network troposphere solutions, days 0-6, for GPS week 937 (free-network beginning week 949)
hirate/JPL0937[0-6].sp3.Z	high-rate (30-s) precise orbits and clocks, days 0-6, GPS week 937
1997.eng.Z	engineering data for 1997, sites in global solution
1997_p.eng.Z	engineering data for 1997, point-positioned sites
ytd.eng	year-to-date engineering data, sites in global solution
ytd_p.eng	year-to-date engineering data, point-positioned sites

Table 3: Other products at ftp://sideshow.jpl.nasa.gov/pub/gipsy_products

Example File	Contents
VeryRapidService/*	hourly Earth orientation, orbits, and clock data for use in GIPSY
RapidService/orbits/jpl0937[0-6].sp3.Z	quick-look precise orbits for days 0-6 (Sun through Sat) of GPS week 937
RapidService/orbits/jpl0937[0-6]_pred.sp3.Z	quick-look 3-day predicted orbit for days 0-6, GPS week 937
RapidService/orbits/1997-12-21.*	daily quick-look and predicted files for use in GIPSY
1997/clocks/1997-12-21.*	1997 daily free- and fixed-network clocks and yaw-rates for use in GIPSY
1997/orbits/1997-12-21.*	1997 daily free- and fixed-network precise orbits, polar motion, shadow-events data for use in GIPSY
hrclocks/1997-12-21.*	high-rate clocks (in TDP format) for use in GIPSY
IERSB/*	IERS Bulletin-B information

Table 4: Addresses of relevant web pages

Address	Contents
http://sideshow.jpl.nasa.gov/mbh/series.html	graphical time-series of site coordinates
http://sideshow.jpl.nasa.gov/mbh/global/table.html	table of site coordinates and velocities
http://milhouse.jpl.nasa.gov/eng/jpl_hp2.html	summaries and plots of station and satellite performance

4 Site Selection

Due to the continuous growth of the global network and the impracticality (with current computer resources) of simultaneously analyzing data from all stations, an algorithm for selecting a well-distributed subset of sites along with required sites such as the IGS fiducials was implemented in late 1994 (see [1]). This scheme chooses N ground stations on the basis of isolation. That is, the Nth site is chosen so as to maximize its distance from the nearest of the N-1 already chosen sites. The RMS isolation **z** (further described in [3]) is used to assess the distribution after all sites have been selected.

The site selection process has evolved since its first implementation, and currently 37 stations are selected as follows:

- Choose a reference clock station (usually NRC1 as of week 936; USNO as of week 955).
- Use 24-hour rapid-service processing results to make a separate list of stations with highly stable clocks. Although these are usually sites with H-masers, in general, these are any stations for which there are at least 250 5-minute clock solutions (out of a maximum of 288) that are smooth at the 4-cm level on timescales of 5 minutes.
- Based on isolation, choose the next 8 most isolated sites from the list of stable clock sites. These will aid in post-processed high-rate clock production.
- Add any sites not yet selected that are fiducial sites and use pseudorange observations (i.e., TurboRogue fiducials). Note that as of GPS week 947, the list of fiducials to choose from is a predetermined, well-distributed 22 station subset of the 47 sites newly designated as IGS fiducials.
- Again based on isolation, choose a number of well-distributed stations using pseudorange (typically TurboRogues), accounting for other fiducials and desired isolated stations not using pseudorange.
- Choose the remaining most isolated stations to complete the 37 total. Ensure that any of these that are of the 47-site IGS fiducial set will be constrained during the fixed-network portion of the processing.

5 Troposphere Products and Strategy Update

Beginning with GPS week 890 (January 26, 1997), JPL began to submit a contribution to the troposphere estimate combination compiled by Gerd Gendt at GFZ. These files contain our daily estimates of the total (wet + dry) zenith tropospheric delay at each site used in the fixed-network global solution. Initially, troposphere parameters were estimated using the Lanyi troposphere mapping function, a satellite elevation cutoff of 15 degrees, and a random walk model with 1.02 cm/sqrt(hr) process noise. The format of the troposphere products was designed by Yoaz Bar-Sever (JPL) and Gerd Gendt, and the JPL solution may be obtained as listed in Table 2.

Starting with GPS week 920 (August 24, 1997), tropospheric gradients were added to the list of parameters estimated for each ground station. In implementing this strategy, the following modifications were made to the estimation process:

- The Niell troposphere mapping function has replaced the Lanyi mapping function.

- Troposphere horizontal delay gradients are estimated at all the stations. The two gradient parameters are modeled as random walk with a sigma of 0.03 cm/sqrt(hour) and are estimated every five minutes.

- The random walk sigma on the estimated zenith wet delay has been reduced from 1.02 cm/sqrt(hour) to 0.30 cm/sqrt(hour).

- The carrier phase post-fit residual rejection criterion has been reduced from 5 cm to 2.5 cm.

- Beginning week 949, troposphere products are representative of the free-network estimates (fixed-network prior to this).

- The elevation angle cutoff has not changed; it remains at 15 degrees. Details of this estimation strategy are presented in [4].

6 New in 1998

Beginning with GPS week 947 (March 1, 1998), JPL adopted IGS procedures set forth at the IGS Analysis Center Workshop in Darmstadt, Germany, February 9-11, 1998 regarding the use of an augmented set of fiducial ground stations and their respective ITRF96 positions. Monument coordinates and velocities are taken from ftp://lareg.ensg.ign.fr/incoming/ITRF96_IGS_RS47.SNX (now available at ftp://igscb.jpl.nasa.gov/igscb/station/coord/ITRF96_IGS_RS47.SNX.Z), and antenna heights from ftp://igscb/igscb/station/general/igs.snx. (Antenna reference point to L1 and L2 phase centers are from ftp://igscb/igscb/station/general/igs_01.pcv.) As only 37 stations are used in the daily analyses, a subset of the 47 sites included in these files is selected as described in section 4 of this document. Moreover, as of this date, SINEX files submitted from JPL contain free-network station coordinates rigorously transformed into ITRF96 via a 7-parameter transformation.

It was also decided at the same AC workshop to eventually discontinue the use of the non-minimal fiducial constraints described above. Therefore, as of GPS week 964 (June 28, 1998), all orbits, clocks, EOP, station coordinates, and relevant statistics reported in our weekly AC summary reports are representative of free-network solutions that are minimally aligned with ITRF96. Only 3 rotations are applied so that geocenter and scale changes can continue to be observed. Also, JPL SINEX files now contain weekly Earth orientation parameters which are consistent with the corresponding sp3-formatted orbits and clocks.

Additionally, a slight change has been made to our automation process. As described in [5], we primarily determine “processing readiness” by periodically calculating the RMS isolation, a measure of the global distribution of available ground sites. As more stations have become a part of the IGS network, in mid-March 1998, we lower the threshold of this value from 2000 km to 1800 km. While this may mean a longer delay in some instances, the four-day maximum wait time is still enforced.

A new set of products for GIPSY users is also now available, namely, hourly GPS ephemeris and clock solutions in the same format as analagous products found in Table 3. These solutions, based on a set of 18 global stations from which hourly data are received, have an accuracy of approximately 1 to 2 meters, and are provided on a “caveat emptor” basis.

7 Results

Figure 1 indicates the further improvement in orbit quality since 1995. As in the past, our metric for orbit quality is the day-to-day consistency of the solutions, i.e., the degree to which estimates from adjacent days agree near the midnight boundaries. Contributing factors are the continuing expansion of the global network, the use of global phase ambiguity resolution, and the estimation of tropospheric gradients.

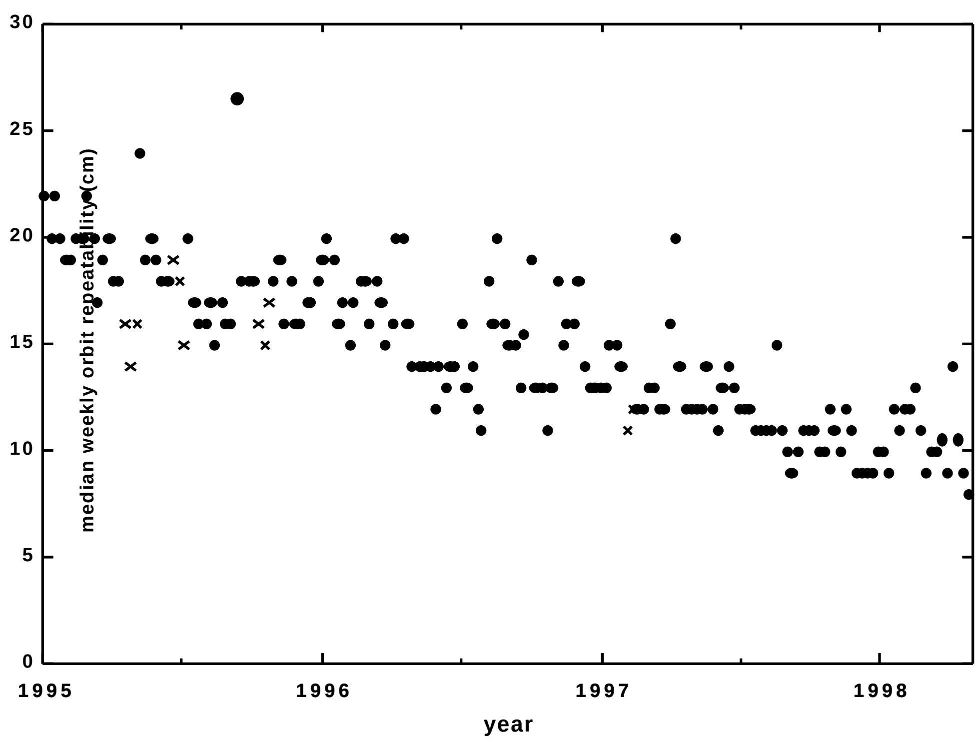

Figure 1: JPL orbit repeatability (3drms) since 1995. Each data point indicates the median over all satellites and days for a particular GPS week. (The daily number for a given satellite indicates the degree to which the precise orbit agrees with those of adjacent days near the midnight boundary.) Weeks during which AS was off are marked with an ‘X’.

8 Acknowledgment

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9 References

[1] J. F. Zumberge, M. B. Heflin, D. C. Jefferson, M. M. Watkins, and F. H. Webb, Jet Propulsion Laboratory IGS Analysis Center 1994 Annual Report, in *IGS 1994 Annual Report*, edited by J. Zumberge, R. Liu and R. E. Neilan, IGS Central Bureau, Jet Propulsion Laboratory, Pasadena CA, 1995, JPL Publication 95-18

[2] M. B. Heflin, D. C. Jefferson, M. M. Watkins, F. H. Webb, and J. F. Zumberge, Comparison of Coordinates, Geocenter, and Scale from All Centers: GNAAC Activities at JPL for weeks 813-897, in *IGS 1996 Annual Report*, edited by J. F. Zumberge, D. E. Fulton, R. E. Neilan, IGS Central Bureau, Jet Propulsion Laboratory, Pasadena, CA, 1997

[3] J. F. Zumberge, M. B. Heflin, D. C. Jefferson, M. M. Watkins, F. H. Webb, Precise point positioning for the efficient and robust analysis of GPS data from large networks, 1997, J. Geophys. Res., Vol. 102, No. B3, p. 5005

[4] Bar-Sever, Y.E., P.M. Kroger and J.A. Borjesson, Estimating Horizontal Gradients of Tropospheric Path Delay with a Single GPS Receiver, 1998, J. Geophys. Res., Vol. 103, No. B3, pp. 5019-5035.

[5] D. C. Jefferson, M. B. Heflin, M. M. Watkins, F. H. Webb, J. F. Zumberge, and Y. E. Bar-Sever, Jet Propulsion Laboratory IGS Analysis Center Report, 1996, in *IGS 1996 Annual Report*, edited by J. F. Zumberge, D. E. Fulton, R. E. Neilan, IGS Central Bureau, Jet Propulsion Laboratory, Pasadena, CA, 1997

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NRCan IGS Analysis Centre Report, 1997

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1 Summary

During 1997, NRCan initiated submission of daily predicted orbits to IGS and participated in the IGS developmental work on the estimation of tropospheric and ionospheric delays. The existing NRCan processing strategy was maintained during 1997 (Tétreault et al., 1996, 1997).

2 Orbit Prediction Strategy

On January 10, 1997 (GPS Week 887), NRCan started contributing daily predicted orbits to the IGS. A 2-day prediction is obtained from 4 IGR rapid orbit solutions by estimating 6 Keplerian elements and 9 radiation pressure parameters using the Bernese software version 3.5. The IGR *x* and *y* Pole position series are used along with the Bulletin A UT1 series to provide the necessary Earth Orientation Parameters. The use of the Bulletin A UT1 series, initiated on GPS Week 934, has improved the z rotation of the NRCan predicted orbits as can be seen in Figure 1. Extrapolations of the EMR and IGR UT1 series were use prior to Bulletin A up to and including GPS Week 916 and 933 respectively. NRCan 2-day predicted orbits are currently about 50-cm median RMS with respect to IGR orbits for non-eclipsing satellites and about 100-cm for eclipsing satellites. Further evaluation of NRCan predicted orbits can be found in [Kouba and Mireault, 1998].

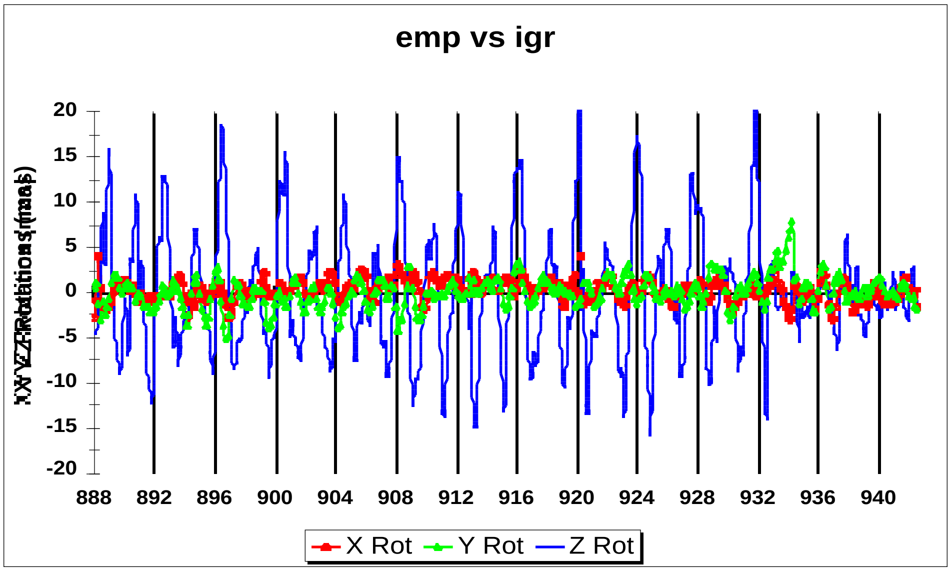


Figure 1. Seven –parameter Helmert transformation between IGR and NRCan Predicted orbits (emp) for GPS Weeks 888 to 943

3 Tropospheric and Ionospheric Modeling

In March 1997, NRCan started contributing to the IGS pilot project for the estimation of tropospheric zenith delay. NRCan estimates tropospheric delays at a 7.5 minute interval using a random walk stochastic model with a 1 $cm/\sqrt{hr}$ sigma. Last epoch estimates from the previous day are weighted and used as apriori values for the current day estimation. For all stations included in NRCan final daily solutions, Total Zenith Delay (TZD) estimates at 2 hour intervals are submitted to IGS on a daily basis (Gendt, 1998).

NRCan, in support of the Canadian Active Control System (CACS) and in preparation for the IGS Ionospheric Pilot Project, has developed a grid model of ionospheric delays. The NRCan regional ionospheric model is based on stations covering the Canadian territory. It is computed using carrier phase smoothed pseudo-range observations with an elevation cut-off angle of 15 degrees and an elevation dependent weighting model. A spherical single layer shell at 350 km elevation and a cosine of the zenith angle mapping function are used. The model is based on 24-hour averages computed in a sun-fixed geographical reference frame. Table 1 presents precise point positioning monthly averages of daily RMS that were achieved using four different processing strategies.

Table 1. Point positioning RMS using NRCan ionospheric modeling

Monthly Averages of Daily RMS
Station NRC1, January 1998
(from position estimates at 15 min. intervals, and using phase smoothed pseudo-range observations)

RMS (m)			Processing Strategy
Latitude	Longitude	Height	
1.3	0.7	3.6	L1
1.0	0.7	1.7	L1 + SLM
0.8	0.4	1.1	L1 + SLM + CAL
0.5	0.4	1.1	L3

L1 = L1 Frequency
SLM = Single Layer Ionospheric Model
CAL = Satellite Differential L1/L2 Code Bias
L3 = Ionospheric Free Combination

4 Final Product Analysis

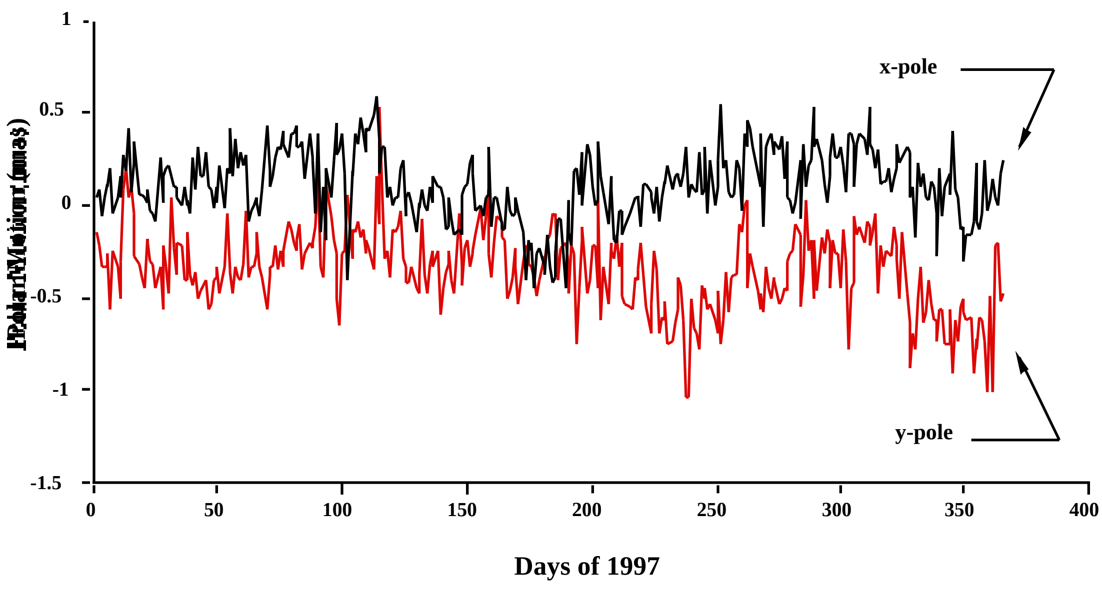
A 2.5-year spectral analysis of the NRCan station position residual series led to the discovery that the use of erroneous ocean loading coefficients were causing a 13.7-day signal. This was corrected on February 23, 1997 and a new spectral analysis for GPS Weeks 894 to 938 confirmed that the 13.7-day signal had been removed.

The consistency of NRCan products was assessed by computing the differences between NRCan and ITRF/IGS products for station coordinates, orbits and EOP's. The estimated 7 parameter transformations are listed in Table 2. UTI-UTC was not included due to its long-term drift, evident in the weekly averaged means and standard deviations. The differences between the IGS and NRCan polar motion and UT1-UTC series are shown in Figures 2 (a) and (b) respectively. The 0.3mas bias seen in the y pole series starting on day 327 was caused by mistakenly over-constraining the weekly station coordinates and EOP combinations for GPS Weeks 933 to 938 inclusively. Weeks 933 to 938 were not used to compute the transformations presented in Table 2.

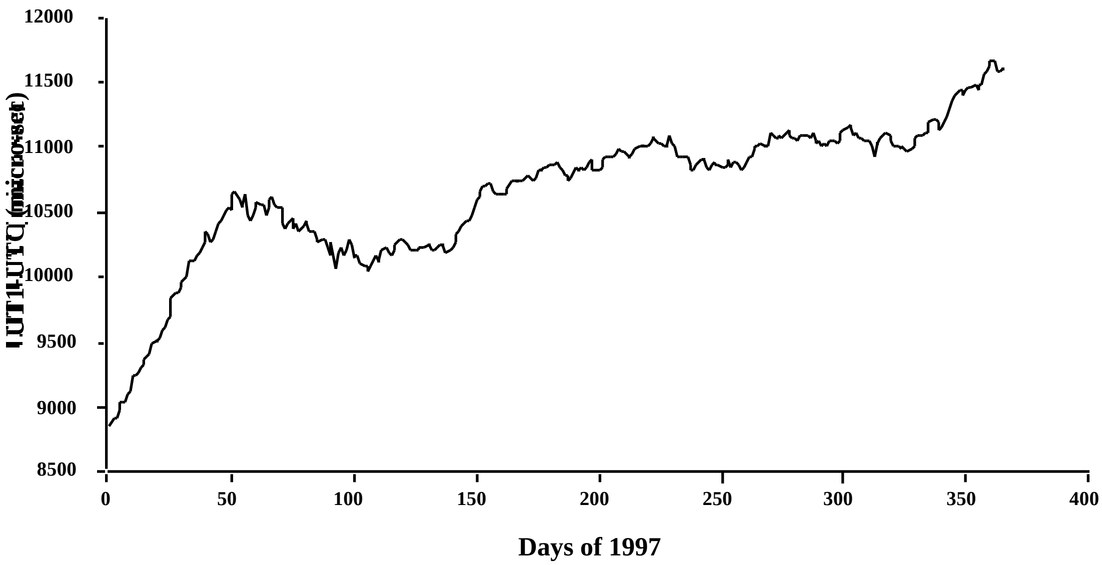
Table 2. Weekly Averaged Differences Between NRCan and ITRF/IGS Products
(NRCan – ITRF/IGS)
(Weeks 886 to 932)

Solution	Translation (cm)			Rotation (mas)			Scale(ppb)
	T1	T2	T3	R1	R2	R3	Sc
Coordinates[a]	0.0	0.4	0.2	0.092	0.017	0.002	-0.47
sigma	0.1	0.2	0.1	0.044	0.025	0.016	0.33
Orbits[b]	0.0	-1.5	-0.4	0.352	-0.072	0.335	-0.08
sigma	0.8	0.9	0.6	0.145	0.129	0.285	0.09
EOP[c]				0.316	-0.116		
sigma				0.142	0.154		

(a) Weekly averaged transformations between the combined NRCan weekly SINEX coordinate solutions and ITRF coordinates for the 13 IGS fiducial stations.
(b) Weekly averaged transformations between NRCan and IGS daily orbits.
(c) Weekly averaged differences between NRCan and IGS daily polar motion.



(a)



(b)

Figure 2. Difference between IGS Final EOP's and NRCan Daily EOP solutions

As in previous years, a multi-year solution of NRCan EOPs, station coordinates and velocities was computed (IERS, 1998). Specifically, the 1997 combination was performed using daily solutions from 1994 to 1997 inclusively. In order to mitigate the small misalignment present in NRCan daily solution, the daily variance-covariance matrices were unconstrained in order to remove the implicit effect of the geocentre prior to the combination. The annual solution was constrained at ITRF96, epoch 1998.0 using stations: ALGO, AREQ, DAV1, DRAO, FAIR, FORT, GOLD, GUAM, HART, IRKT, KERG, KIT3, KOKB, LHAS, MADR, SANT, TIDB, TROM, TSKB, WTZR, YAR1 and YELL.

5 References

Gendt, G., (1998), IGS Combination of Tropospheric Estimates – Experience from Pilot Project, 1998 Analysis Center Workshop Proceedings (edited by J. Dow, J. Kouba and T. Springer) February 9-11, Darmstadt, Germany (in print)

IERS, (1998), Annual Report for 1997, Central Bureau of IERS, Observatoire de Paris, Paris, France, 1998

Kouba, J. and Y. Mireault,(1998), "1997 Analysis Coordinator Report", 1997 IGS Annual Report, IGS Central Bureau, Pasadena, CA (this volume)

Tétreault, P., C. Huot, R. Ferland, J. Kouba and J. Popelar,(1997), "NRCan Analysis Centre Annual Report for 1996", 1996 IGS Annual Report, IGS Central Bureau, Pasadena, CA, November 1997, pp. 221-232

Tétreault, P., R. Ferland, J. Kouba and J. Popelar,(1996), "NRCan (EMR) Analysis Centre 1995 Annual Report to the IGS", 1995 IGS Annual Report, IGS Central Bureau, Pasadena, CA, September 1996, pp. 175-186

Scripps Orbit and Permanent Array Center
1997 Analysis Center Report

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1 Introduction

The Scripps Orbit and Permanent Array Center (SOPAC) at the Scripps Institution of Oceanography has been providing precise satellite ephemerides and Earth orientation parameters since 1991. The development of the Permanent GPS Geodetic Array (PGGA) in southern California at that time served as a catalyst for the generation of precise GPS orbits, and continues to be a catalyst with the development of the Southern California Integrated GPS Network (SCIGN).

This report will focus on SOPAC's analysis procedures and reprocessing of early IGS products. The 1997 annual report of the SOPAC Global Data Center is in a separate document.

2 Products Submitted

IGS data and products are available at SOPAC's GARNER archive, which is accessible through anonymous ftp (ftp://ftp.lox.ucsd.edu) or via our homepage (http://lox.ucsd.edu). To retrieve SIO products via ftp, change directory to /pub/products, and select the appropriate GPS week. The following SOPAC analysis products are contributed to the IGS:

Type of Product	File Format	Description
Final Products	SIOwwwwn.SP3	Daily ephemeris files
	SIOwwww7.ERP	Weekly EOP (pole, UT1-UTC, lod)
	SIOwwww7.SUM	Weekly processing summary
	SIOwwww7.SNX	Weekly SINEX files
Rapid Products	SIRwwwwn.SP3	Daily rapid orbit solutions
	SIRwwwwn.ERP	Daily rapid EOP solutions
Prediction Products	SIPwwwwn.SP3	24 hour orbit predictions
	SIPwwwwn.SP3	48 hour orbit predictions

The final products are generally available within 4 days of the end of the GPS week; the rapid and prediction products are available within 18 hours of the end of the UTC day. The daily processing volume at SOPAC is about 280 stations per day.

3 Reprocessing of IGS Products (1992-1995)

During 1997 a major effort was made to reprocess GPS data from as early as June 1992. Improvements and changes in analysis software and processing algorithms makes the coordinate time series, precise ephemerides, and EOP inconsistent over longer periods of time and results derived by them may be biased. Therefore, we reanalyzed IGS data between June 1992 and June 1995. The results are a significant improvement in our site position time series, orbit ephemerides and EOP. Also, problems encountered during this reanalysis were recorded so that future reprocessing campaigns will be as smooth as possible and therefore, less time consuming.

Since changes in the software are continuously made, re-analysis of earlier data after major improvements is necessary to acquire the best products possible. The next reprocessing which will commence in 1998 will also include data obtained before June 1992.

4 Site Selection

Various new sites were added to the IGS network in 1997. As a result, the amount of sites contributing to the daily solution increased slightly to approximately 60 per day at the end of 1997 (Figure 2). The stations used by SOPAC in the global processing are shown in Figure 1.

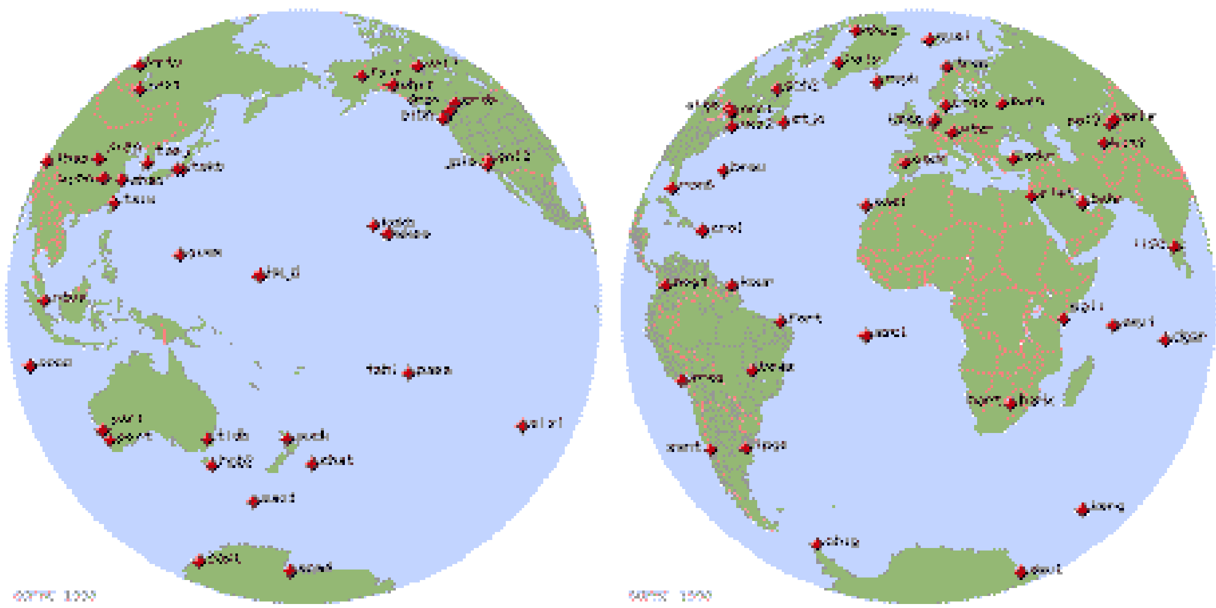

Figure 1. IGS stations processed by SOPAC

To ensure fast turn around of the rapid solution, the number of stations in this solution was limited to 47 (Figure 2), but new sites of better quality and latency were incorporated in the rapid analysis schemes to ensure higher reliability. The days for which data of less than 40 sites were available for the rapid analysis were mostly correlated with weekends. The latency of the data during this time is apparently worse than during the work week. The availability of SIO's rapid solution has improved (Figure 2) and is generally available within 18 hours after the end of the day.

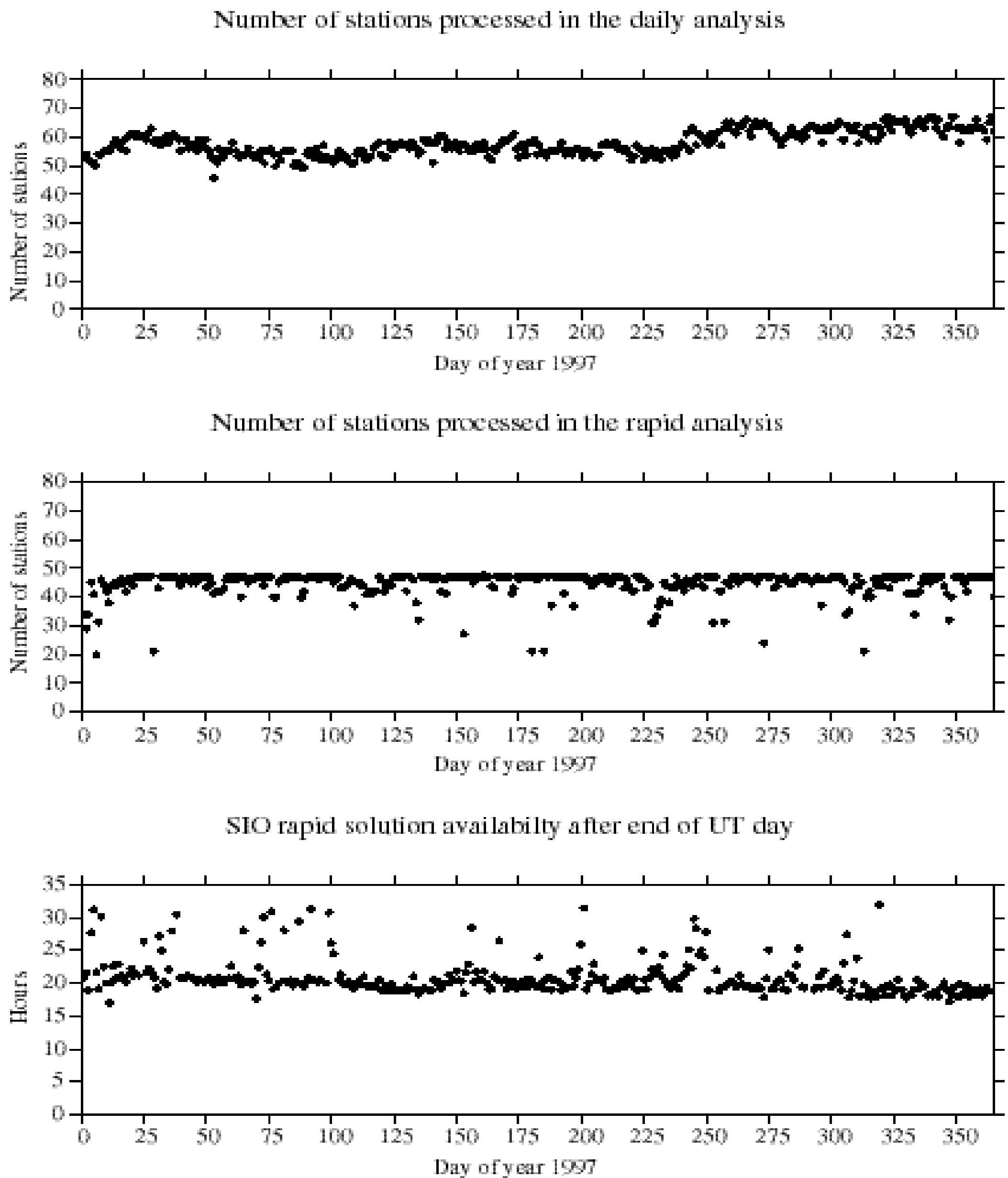

Figure 2. Number of sites included in the daily and rapid SIO analysis during 1997 and the availability of the rapid solution after the end of the UTC day.

5 Analysis Procedure

SIO continues to use a multi-day processing scheme in distributed mode for its rapid and predicted solutions. The primary reason for doing distributed processing is to increase processing efficiency by dividing a large network into smaller subnetworks. For SIO's rapid and predicted solutions, the global network is divided into two subnetworks with 5 stations in common to provide sufficient overlap when the two solutions are combined at a later stage. For these 5 common stations, there are a few near-by stations chosen as backup in the event that any of these stations' data are not available. In order to maintain a uniform processing speed, the maximum number of stations of each subnetwork is limited to 26 which are chosen to best suit our processing hardware configuration without sacrificing product quality.

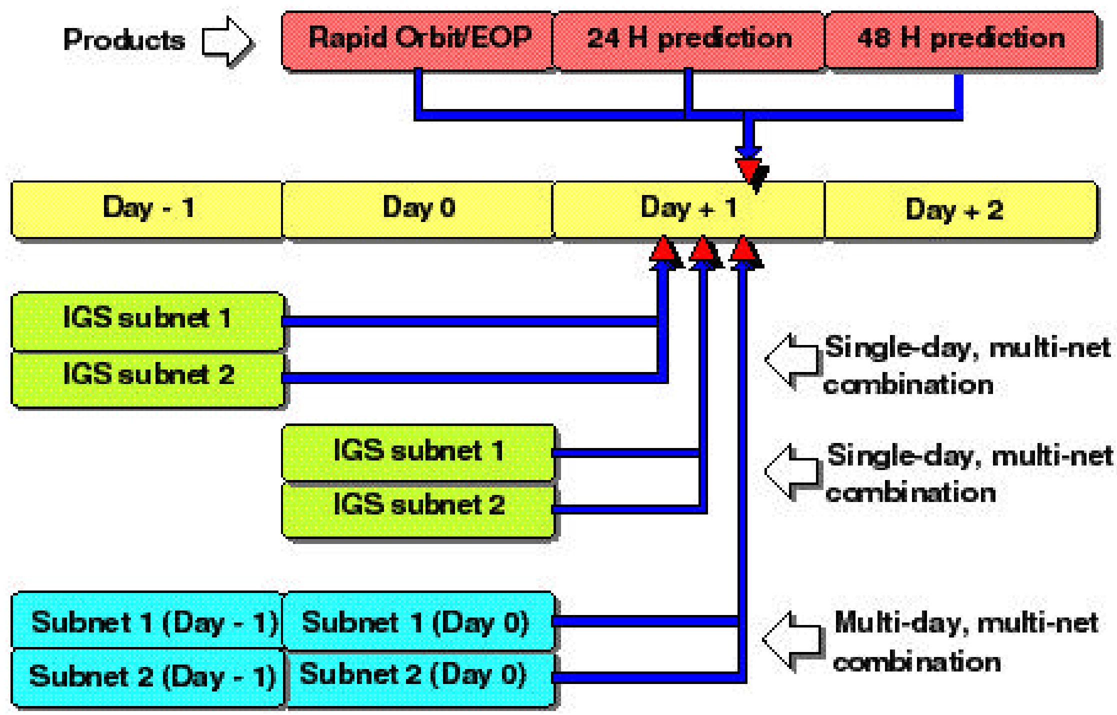

Figure 3. Processing timeline for SIO rapid and predicted solutions

Since the total number of IGS global stations is growing steadily, our processing procedure uses a prioritized station selection scheme to ensure the use of the stations that are most evenly distributed and of the highest data quality. In this scheme, good geographical location bears highest weight. This fully automated procedure and its execution timeline are illustrated in Figure 3. During processing, tight constraints are imposed on *a priori* values of ITRF96 coordinates and the UT1 values from IERS Series 7 obtained from USNO weekly (later biweekly) submissions. The main adjusted parameters are station coordinates, orbital parameters, pole-x, pole-y positions, and LOD. In addition, tropospheric delay parameters are estimated at one-hour intervals for each station. The time for orbital initial conditions (IC) is set to the midday of day 0 for both day-1 and day 0 solutions. The solutions are performed with the GAMIT software package incorporating a weighted least square approach. These two sets of 24 hour solutions on individual subnetworks are then combined with the GLOBK software incorporating a Kalman filter approach. The resulting orbits and EOP become SIO rapid products. Once the rapid orbits and EOP are generated, they are used for orbit extrapolation (through integration) further into 24 and 48 hour predicted orbits. Then the rapid orbits and EOP together with 48-hour predicted orbits are submitted to the IGS for its combination solutions. The 24-hour predicted orbits are sent to the SIO data/product server to replace the previous day's 48-hour predicted orbits. This particular arrangement has been proven very useful since many near real-time users who themselves have some data collection delays may take advantage of 24 hour predictions as they are of higher quality than 48 hour predictions. The 24-hour predicted orbits are also used as the next day's *a priori* orbits.

SIO's regular daily solution is carried out in distributed mode. Compared to the rapid solutions, the regular daily solutions are single-day solutions. The maximum number of stations in a subnetwork is set to 42 in order to include as many global stations as possible. The latency of the daily solutions is between 4 to 6 days. The main reason for this delay is to wait for more data and to take advantage of better *a priori* UTC values. The rapid orbits serve as *a priori* orbits for the regular daily solutions. The selection of stations in the global network is mainly dictated by geographical distribution. Regions with higher concentrations of stations are grouped into regional networks, such as Europe (designated as EURA), California (PGGA, DGGA, BARD), and U.S. (CORS). The CORS array is processed primarily to obtain tropospheric delay estimates at frequent time intervals (every 30 minutes).

SIO's final weekly solution is generated after 7 regular daily solutions are completed. This solution, employing a Kalman filter approach with GLOBK, uses a set of covariance matrices from unconstrained daily solutions of both global and regional subnetworks, tightly constraining a set of core IGS stations defined in ITRF96, to estimate station positions, orbits, and EOP. It should be noted that the unconstrained solutions are produced in the same GAMIT runs as the constrained solutions.

Detailed description on the modeling of parameters and other strategic settings are given in the IGS data processing center questionnaire (see appendix), also available at IGS Central Bureau homepage (http://igscb.jpl.nasa.gov).

Regional networks are processed with orbital parameters tightly constrained after corresponding global solutions becomes available. The relationship among the above-mentioned processes is depicted in Figure 4. (The real-time sliding window is tested but not yet operational).

Since January 15, 1996, all SIO solutions adapted the Neill mapping function [Niell, 1996] to replace the CFA 2.2 mapping function. At the same time, the elevation angle cutoff was lowered from 15° to 7°.

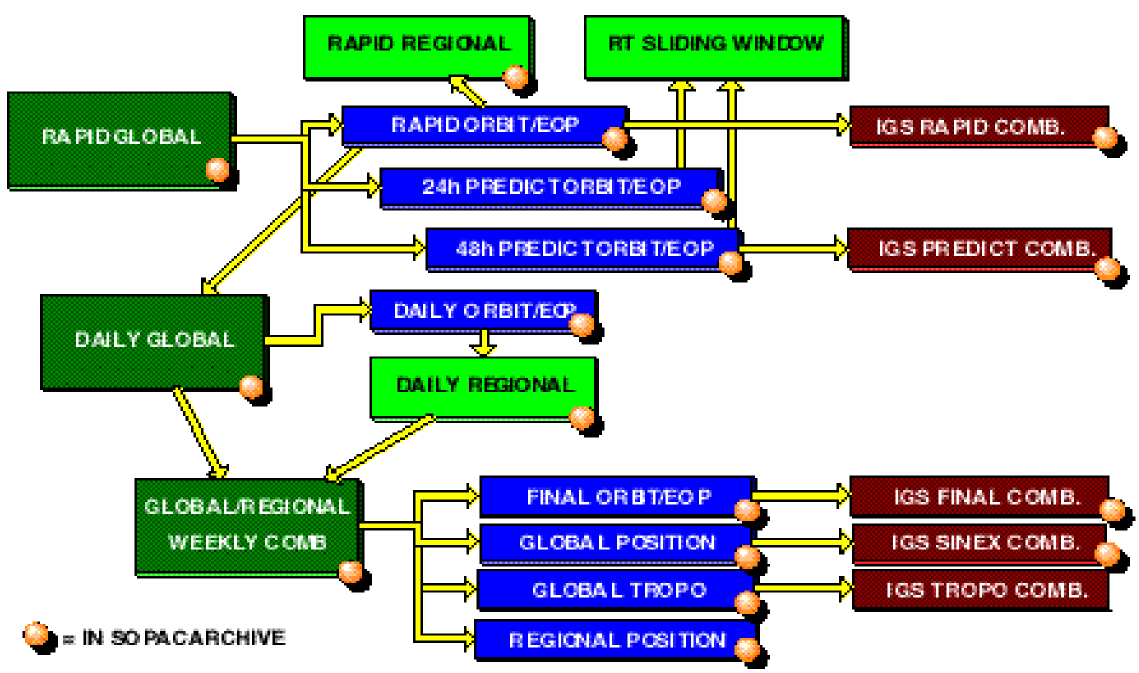

Figure 4. The relationship of various processing elements and their products.

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8 References

Ash, M. E., Determination of Earth satellite orbits, Tech. Note 1972-5, Lincoln Laboratory, MIT, 19 April 1972.

Bar-Sever, Y. E., A new module for GPS yaw attitude, in Proc. IGS Workshop: Special Topics and New Directions, edit. G. Gendt and G. Dick, pp. 128-140, GeoForschungsZentrum, Potsdam, 1996.

Beutler, G. (1990). Numerische Integration gewoehnlicher Differentialgleichungssysteme: Prinzipien und Algorithmen. Mitteilungen der Satelliten-Beobachtungsstation Zimmerwald, No. 23, Druckerei der Universitat Bern, 1990.

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

Dong, D., and Y. Bock, Global Positioning System network analysis with phase ambiguity resolution applied to crustal deformation studies in California, Journal of Geophysical Research, 94, 3949-3966, 1989.

Feigl, K. L., and 14 others, Space geodetic measurement of crustal deformation in central and southern California, 1984-1992, Journal of Geophysical Research, 98, 21,667–21,712, 1993.

Herring, T. A., GLOBK: Global Kalman filter VLBI and GPS analysis program Version 4.17, Internal Memorandum, Massachusetts Institute of Technology, Cambridge, 1998.

Herring, T. A., and D. Dong, Measurement of diurnal and semi-diurnal rotational variation and tidal parameters of the Earth, Journal of Geophysical Research, 99, 18,051, 1994.

King, R. W., and Y. Bock, Documentation of the GAMIT GPS Analysis Software version 9.72, Mass. Inst. of Technol., Cambridge, 1998.

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

McCarthy, D. D. (ed.) (1996). IERS Conventions (1996). IERS Technical Note 21, Observatoire de Paris, July 1996.

Niell, A. E., Global mapping functions for the atmospheric delay, J. Geophys. Res., 101, 3227-3246, 1996.

Schaffrin, B., and Y. Bock, A unified scheme for processing GPS phase observations, Bulletin Geodesique, 62, 142–160, 1988.

Springer, T. A., G. Beutler, and M. Rothacher, A new solar radiation pressure model for the GPS satellites, IGS Analysis Center Workshop, Darmstadt, 9-11 February 1998.

Wu, J. T., S. C. Wu, G. A. Hajj, W. I. Bertiger, S. M. Lichten, Effects of antenna orientation on GPS carrier phase. Manuscripta Geodaetica 18, 1993, 91-98, 1993.

APPENDIX

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                   INTERNATIONAL GPS SERVICE FOR GEODYNAMICS

                       SOPAC Processing Strategy Summary


==============================================================================
Analysis Center    | Scripps Orbit and Permanent Array Center (SOPAC),
                   | Institute of Geophysics and Planetary Physics (IGPP),
                   | Scripps Institution of Oceanography (SIO),
                   | University of California, San Diego (UCSD)
                   |
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                   | Matthijs van Domselaar   e-mail: mvandomselaar@ucsd.edu
                   |                          phone : ++ 1 619 534 2031
------------------------------------------------------------------------------
Software Used      | GAMIT v. 9.72, GLOBK v. 4.17,   developed at MIT/SIO
------------------------------------------------------------------------------
Final Products     | siowwwwn.sp3    GPS ephemeris files in 7 daily
generated for      |                 files at 15 min intervals in SP3 format,
GPS week 'wwww'    |                 including accuracy codes computed from
day of week 'n'    |                 overlapping analysis wrt. previous day.
(n=0,1,...,6)      | siowwww7.erp    ERP (pole, UT1-UTC) weekly solution
                   | siowwww7.sum    Summary of weekly solution combining both
                   |                 IGS global and regional solutions.
                   | siowwww7.snx    Weekly coordinates in SINEX format
                   | siowwwwn.tro    Daily files of 1-h troposphere delay
                   |                 estimates in SINEX format (based
                   |                 on 1-day solutions).
Rapid Products     | sirwwwwn.sp3    Daily orbits for current-1 day. ~16 hour
                   |                 delay.
                   | sirwwwwn.erp    Daily EOP for current-1 day. ~16 hour
                   |                 delay.
Predictions        | sipwwwwn.sp3    24 hour predicted orbits. Partially
                   |                 real-time. This file will replaces 48 hour
                   |                 predicted orbits of previous day upon
                   |                 generation.
                   | sipwwwwn.sp3    48-hour real-time predicted orbits
                   |
------------------------------------------------------------------------------
Preparation Date   | July 13, 1998
------------------------------------------------------------------------------
Effective Date for| May 31, 1998
Data Analysis      |
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MEASUREMENT MODELS	
Observable	Doubly differenced, ionosphere-free combination of L1 and L2 carrier phases. Pseudoranges are used only to obtain receiver clock offsets and in ambiguity resolution.
Data weighting	Sigma on doubly difference LC phase: 64 mm Sampling rate: 2 minutes Elevation angle cutoff : 7 degrees
Data Editing	Cycle slip fixing is performed at one-way level using a combination of one-way and double-difference observations. If a cycle slip cannot be fixed reliably, the data observation is flagged and an additional bias parameter estimated implicitly in the solution.
RHC phase rotation corr.	Phase polarization effects applied (Wu et al, 1993)
Ground antenna phase center calibrations	Elevation-dependent phase center corrections are applied according to the model IGS_01. The corrections are given relative to the Dorne Margolin T antenna.
Troposphere	A priori zenith delay: nominal constant; sub-daily corrections estimated as described below
	Met data input: none
	Mapping functions: (Niell, 1996)
Ionosphere	Not modeled (ionosphere eliminated by forming the ionosphere-free linear combination of L1 and L2).
Plate motions	ITRF96 velocities (see position constraints in estimated parameters and reference frame below)
Tidal displacements	Solid earth tidal displacement: constant Love number tides frequency dependent radial tide (K1)
	Pole tide: not applied
	Ocean loading: not applied
Atmospheric loading	Not applied
Earth orientation	IERS Bulletin A plus diurnal and semidiurnal variations in x,y, and UT1 models (EOP) using VLBI based model

	of Herring and Dong (1994); daily corrections to UT1 rate, pole position and rate estimated as described below
Satellite center of mass correction	Block I x,y,z: 0.2100, 0.0000, 0.8540 m
	Block II/IIA x,y,z: 0.2794, 0.0000, 0.9519 m
	Block IIR x,y,z: -0.0031,-0.0012, 0.0000 m
Satellite phase center calibrat	Not applied
Relativity corrections	Relativistic corrections applied
GPS attitude model	Yaw computed using model of Bar-Sever (1996), using nominal rates or estimates supplied by JPL

ORBIT MODELS	
Geopotential	GEM T3 degree and order 8
	GM = 398600.4415 km**3/sec**2
	AE = 6378.1363 km
Third-body	Sun and Moon as point masses
	Ephemeris: CfA PEP NBODY 740
	GMsun = 132712440000 km**3/sec**2
	GMmoon = 4902.7989 km**3/sec**2
Solar radiation pressure	A priori: nominal block-dependent constant direct acceleration; corrections to direct, y-axis, and B-axis constant and once-per-rev terms estimated (see below) (Beutler et al., 1994; Springer et al. 1998)
	Earth shadow model: umbra and penumbra
	Earth's albedo: not applied
	Satellite attitude model not applied
Tidal forces	Solid earth tides: frequency independent Love’s number K2= 0.300
	Ocean tides: UT CSR model (IERS 1996)

Relativity	Applied (IERS 1996, Chapter 11, Eqn.1)
Numerical Integration	Adams-Moulton fixed-step, 11-pt predictor-corrector with Nordsieck variable-step starting procedure (see Ash, 1972 and references therein)
	Integration step-size: 75 s; tabular interval: 900 s
	Arc length: 24 hours

ESTIMATED PARAMETERS (A PRIORI VALUES & SIGMAS)	
Adjustment	Batch weighted least squares
Station coordinates	Up to 50 IGS stations for rapid solutions Up to 80 IGS stations for regular daily solutions
Satellite clocks bias	Time fixed from Broadcast ephemeris; phase variations estimated for editing only, eliminated in solution by double differencing
Receiver clock bias	Time estimated from pseudoranges phase variations estimated for editing only, eliminated in solution by double differencing
Orbital parameters	6 Keplerian elements plus 9 radiation-pressure terms: constant and sin/cos once-per-rev terms for a direct, y-axis, and b-axis acceleration; all but direct and y-axis constant term constrained to 1% of zero
Troposphere	Knots of a linear spline in zenith delay estimated once per hour for each station constrained by a random-walk process to 2 cm/sqrt(hr); one N-S and one E-W gradient parameter per day for each station, constrained to 3 cm at 10 deg elevation angle
Ionospheric correction	Not estimated (first-order effect eliminated by linear combination of L1 and L2 phase)
Ambiguity	Resolution attempted for baselines < 500 km using phase with an 8 ppm ionospheric constraint and pseudo-range (Dong & Bock, 1989; Feigl et al., 1993)
Earth Orient. Parameters (EOP)	Pole X/Y and their rates, and UT1 rate estimated once per day.
GPS attitude model	Not estimated

REFERENCE FRAMES	
Inertial	Geocentric; mean equator and equinox of 2000 Jan 1 at 12:00 (J2000.0)
Terrestrial	ITRF96, with 37 stations constrained 2-3 mm in horizontal and 10-14 mm in vertical coordinates)
Interconnection	Precession: IAU 1976
	Nutation: IAU 1980