IGS

ANALYSIS CENTER REPORTS

2001/2002 Analysis Coordinator Report

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Introduction

This report complements the Analysis Activities Report given in the IGS Annual Report 2001/2002 (Weber, 2003). A summary of the most important model changes and IGS Analysis Activities in 2001/2002 will be presented.

IGS Product Quality

The primary objective of the IGS is to provide a Reference System for a wide variety of GPS applications. To fulfil this role the IGS produces a large number of different combined products which constitute the practical realization of the IGS Reference System. Table 1 shows the estimated quality of the provided data sets at the end of year 2002.

Table 1: Quality of the IGS products as of December 2002
(for details see http://igscb.jpl.nasa.gov/components/prods.html)

Products / Delay	Ultra-Rapid/ Real Time	Rapid/ 17 hours	Final/ 13 days	Units
Orbit (GPS)	15.0	5.0	3.0	cm
Satellite Clocks	5.0 (predicted)	0.1	0.05	ns
Station Clocks		0.1	0.05	ns
Orbit (GLONASS)	----	----	25.0	cm
Polar Motion		30.0	0.05	mas
LOD			20.0	μs/d
Stations h/v			3.0/6.0	mm
Troposphere			4.0	mm ZPD

IGS Final Orbits

Figure 1 shows the weighted orbit RMS (WRMS) of the Final Analysis Centre solutions with respect to the combined IGS final orbit products from 1994 until end of 2002. The graphic nicely demonstrates past and still ongoing improvements in modelling satellite orbits. Most Analysis Centres and also the IGS rapid orbits (IGR) have reached the 3-6 centimeter precision level (Table 2). Similar levels of accuracy are indicated by the IGS 7-day arc orbit analysis and by comparisons with satellite laser ranging measurements to the GPS satellites PRN 5 and PRN 6.

Table 2: Yearly average weighted orbit RMS (cm) of the Final Analysis Center orbit submissions and the IGS Rapid (IGR) orbit solution with respect to the IGS final orbits

Year	COD	EMR	ESA	GFZ	JPL	NGS	SIO	IGR
Final 2002	2	4	6	2	3	8	5	2

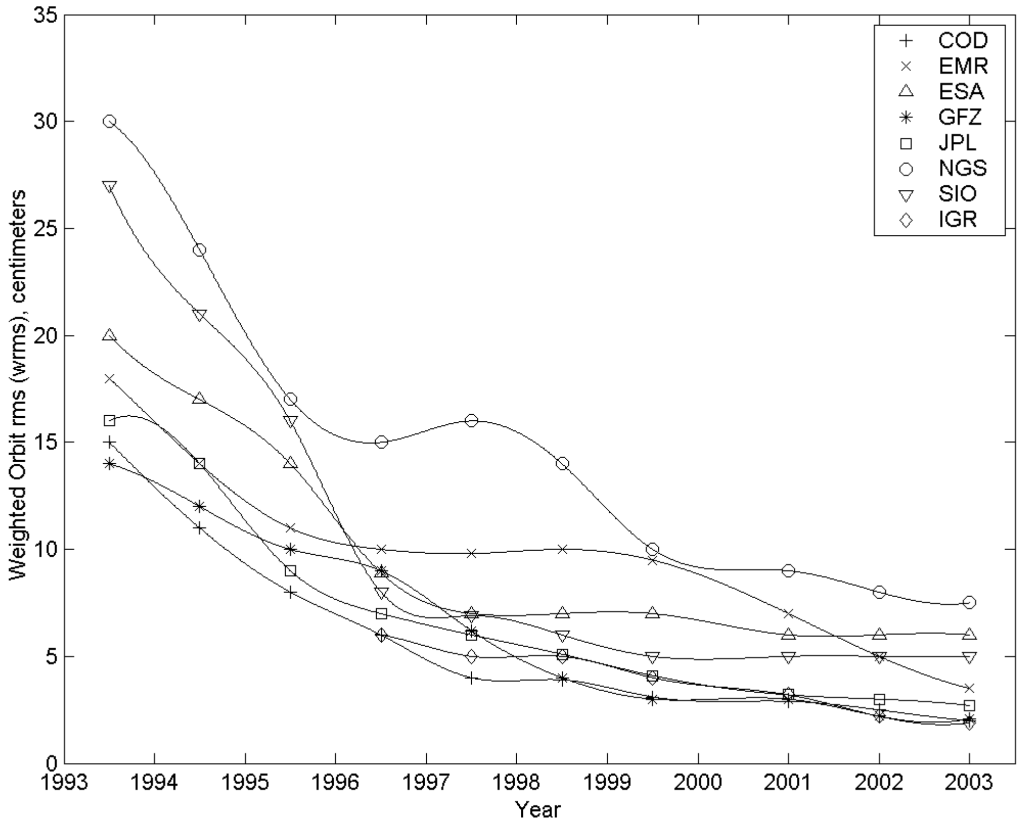

Figure 1: Weighted orbit RMS (WRMS) of the Analysis Center and the IGS Rapid (IGR) orbit solutions with respect to the IGS final orbits; WRMS values were smoothed for graphical representation

Detailed Information concerning quality and availability of Precise Glonass orbits is provided in the report of the International GLONASS Service – Pilot Project (this Volume).

IGS Rapid Orbits

The IGR-orbit is routinely compared to the IGS orbit. Although not entering with any weight in the Finals orbit combination the IGR orbit turns out to be as close to the IGS orbit as the best final AC solutions or even closer (1-2cm; see Table 2).

Table 3: Yearly average weighted orbit RMS (cm) of the Rapid Analysis Center submissions with respect to the IGS Rapid orbit combination.

Year	COD	EMR	ESA	GFZ	JPL	NGS	SIO	USN
Rapid 2002	3	5	8	5	4	8	6	3

Table 3, along with Figure 2, show the weighted RMS (mm) of the individual AC solutions with respect to the IGS Rapid orbit in 2002. For display purposes the values of the Rapid Combination summaries are smoothed using a sliding 7 day window. The orbit consistency ranges between 3-8 cm, which are quite small numbers having in mind the latency of only 17 hours causing a relatively low amount of available tracking data.

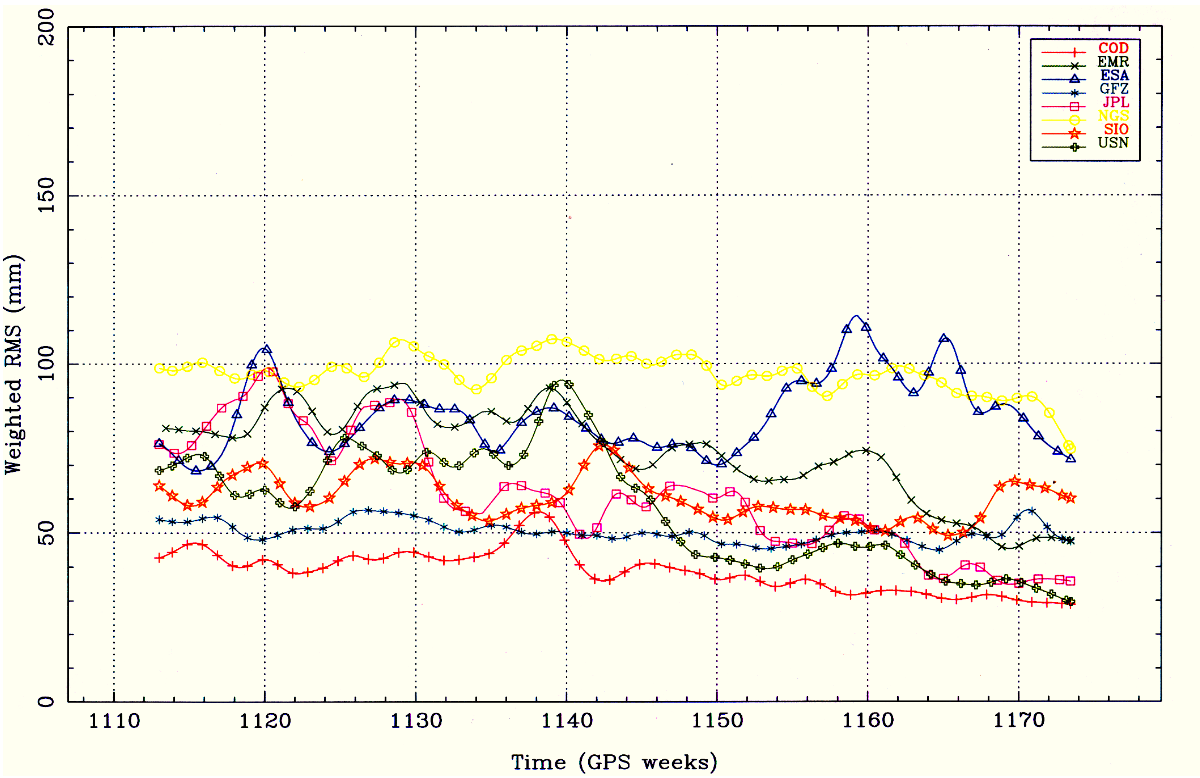

Figure 2: Weighted orbit RMS (WRMS) of the Analysis Center Rapid orbit solutions and the IGR orbit solutions with respect to the IGS final orbits (mid 2001 until mid 2002)

IGS Clock Combination

The consistency of the final AC clock solutions is at the 0.05 ns level, the consistency of the rapid clock solutions slightly better than 0.1 ns (see Figure 3). The combined final and rapid solutions provide satellite and station clock information with a temporal spacing of 5 minutes. An even higher resolution (30 seconds) is recommended, and foreseen to be provided in the near future. This will put a remarkable additional computation load at the ACs.

The basic clock combination proofed to be a very robust process. After combination the IGS combined clock products are aligned to GPS time (broadcast satellite clock corrections) on a daily basis. This procedure sometimes fails due to jumps of the reference clock of individual AC's. Moreover the alignment introduces significant daily discontinuity errors up to a few nanoseconds. To mitigate the problem the IGS clock products will be aligned to the UTC time scale in the near future (see Senior et al., 2001)

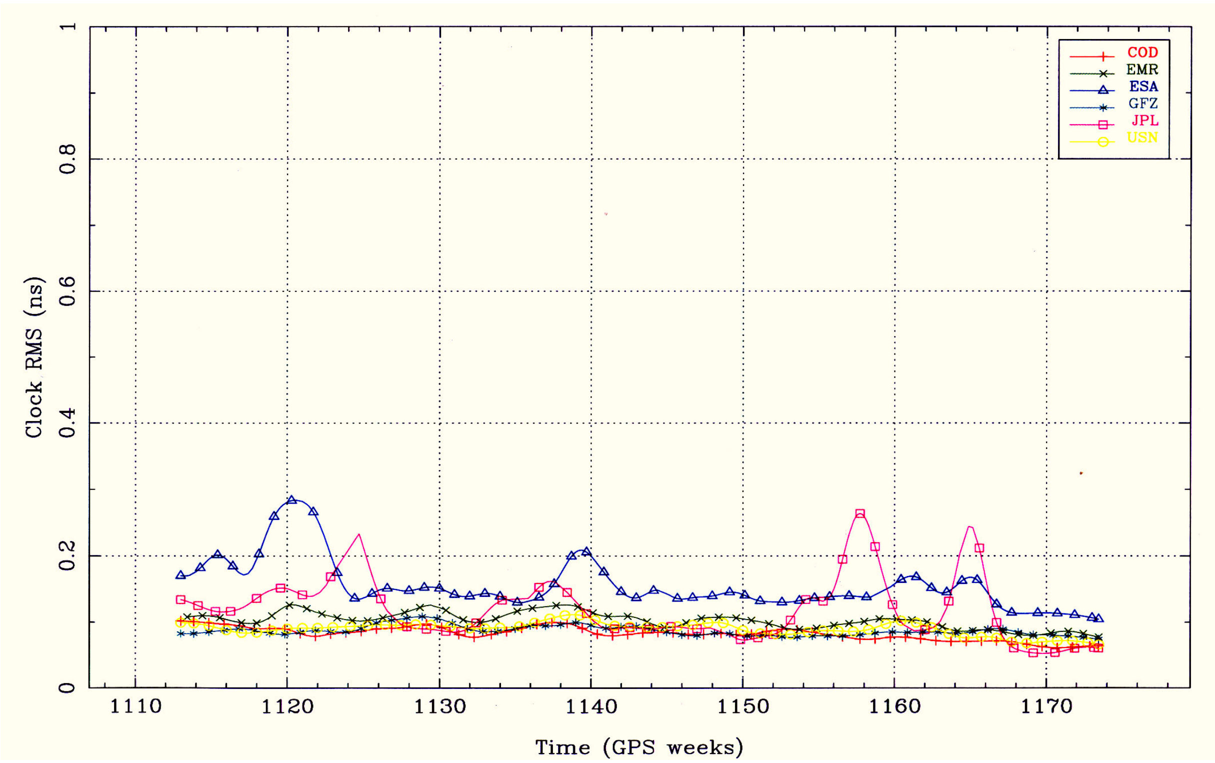

Figure 3: Clock RMS (ns) of the individual AC satellite clock solutions with respect to the IGS Rapid clocks (mid 2001 until mid 2002).

Reference Frame

Since December 2001 (GPS-Week 1143) all IGS products are based consistently on the IGS Reference Frame realization (IGS00) of the ITRF2000. To perform this task the unconstrained weekly combined IGS-SINEX solution of station coordinates/velocities and ERP's is aligned by minimum datum constraints to IGS00, based on a list of 54 reference stations with high quality positions/velocities in ITRF2000. Previous to the combination also the individual orbit solutions are rotated by means of a spatial similarity transformation to this common frame. IGS reference frame products are available in SINEX format and issued by the IGS Reference Frame Coordinator on a weekly basis. Detailed information can be obtained from (Ferland, 2001) or from the weekly IGS SINEX Combination Reports (e.g. Ferland, Hutchison, 2001).

Earth Rotation Parameters

Although the IGS final combination establishes another weighted erp-file based on orbit quality, the 'official' IGS pole series stem from the weekly SINEX combination performed at NRCan. IERS comparisons show an agreement between IGS and IVS solutions at the 0.1mas level for polar motion (PM) and 0.1ms for Length of Day (LOD). It has to be stated that Bulletin B erp-series are dominated by VLBI although there are differences at the same level (0.1mas,0.1ms) between IVS solutions using different observation networks. IGR erp-series be given a heavy weight in the Bulletin A combination and are therefore close (0.05mas PM, 0.1ms LOD) to the Bulletin series. An IERS recommendation, passed at the IERS Workshop in Munich (November 2002), encourages all IGS AC's to provide in addition to polar motion and LOD also nutation rate series.

Atmosphere Sounding Products

Detailed Information concerning quality and availability of IGS Atmosphere Sounding Products is provided in the reports of the relevant Working Groups (this Volume).

IGS Ultra Rapid Products

In October 1999 the GFZ Analysis Centre provided the first ultra rapid products. These products, delivered every 12 hours (two times per day), contain a 48 hour orbit arc from which 24 hours are real orbit estimates and 24 hours are orbit predictions. The latency of this product is 3 hours. The generation of a combined 'ultra-rapid' product (IGU) has started in March 2000 based on contributions from up-to six different Analysis Centres. Currently IGU orbits are used in an increasing number of applications, e.g. for the derivation of ground-based GPS meteorological parameters used in numerical weather prediction or in regional GNSS Reference Network solutions used for RTK surveying.

IGU Orbits

The orbit consistency level, characterized by the weighted orbit RMS (WRMS) of the observed part of ultra rapid Analysis Center solutions with respect to (w.r.t.) the combined IGS Ultra-Rapid Orbit (IGU) ranges from 10-25 centimetres (see Figure 4). The predicted part of the IGU compares to the IGR orbit at the 30 cm level.

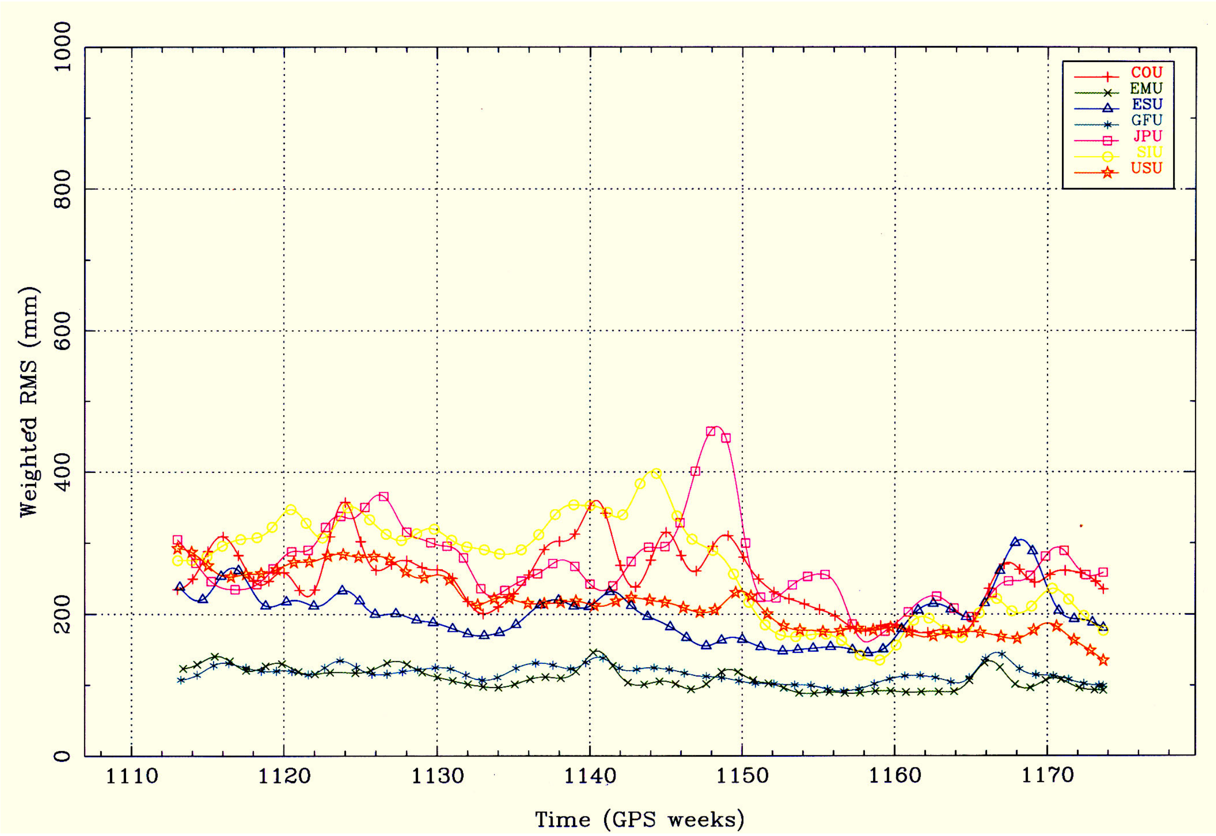

Figure 4: Weighted orbit RMS (WRMS) of the Analysis Center Ultra Rapid orbit solutions with respect to the IGS Rapid orbits (mid 2001 until mid 2002)

IGU Satellite Clock Corrections

As mentioned above, the IGU orbits and clock corrections are the result of a weighted averaging process, currently based on individual submissions of 6 IGS Analysis Centres. Most of these solutions contain 24 hours of observed clock corrections consistent with the provided orbits and 24 hours of clock extrapolation. We were interested in a rough estimate of the overall quality of the individual AC clock submissions. A raw comparison of the observed and the predicted clock-offsets w.r.t. the combined IGS Rapid clock solution is given in Figures 5 and 7. The calculations are based on the clock information given in the sp3-product files with a time resolution of 15 minutes. Thus the time axis in these diagrams cover 96 epochs over a day (E1-E96).

Raw clock differences usually reflect the clock offset and the clock drift of clock 2 w.r.t. reference clock 1. In contrast to the combined IGS Rapid clock product (linearly aligned to GPS-time) the reference clocks used in AC solutions are steered to a very stable clock at one of the tracking sites or to a weighted assembly of hydrogen masers located in timing laboratories around the world. A clock-offset and the clock-drift are common to all reported satellite clocks. In addition clock-differences may reflect radial orbit differences (per satellite) of the corresponding ephemeris, which propagate into the clock solutions. For the observed 24 hours part these differences induced by the orbits usually range up to a few tenth of a nanosecond (1 ns = 30 cm).

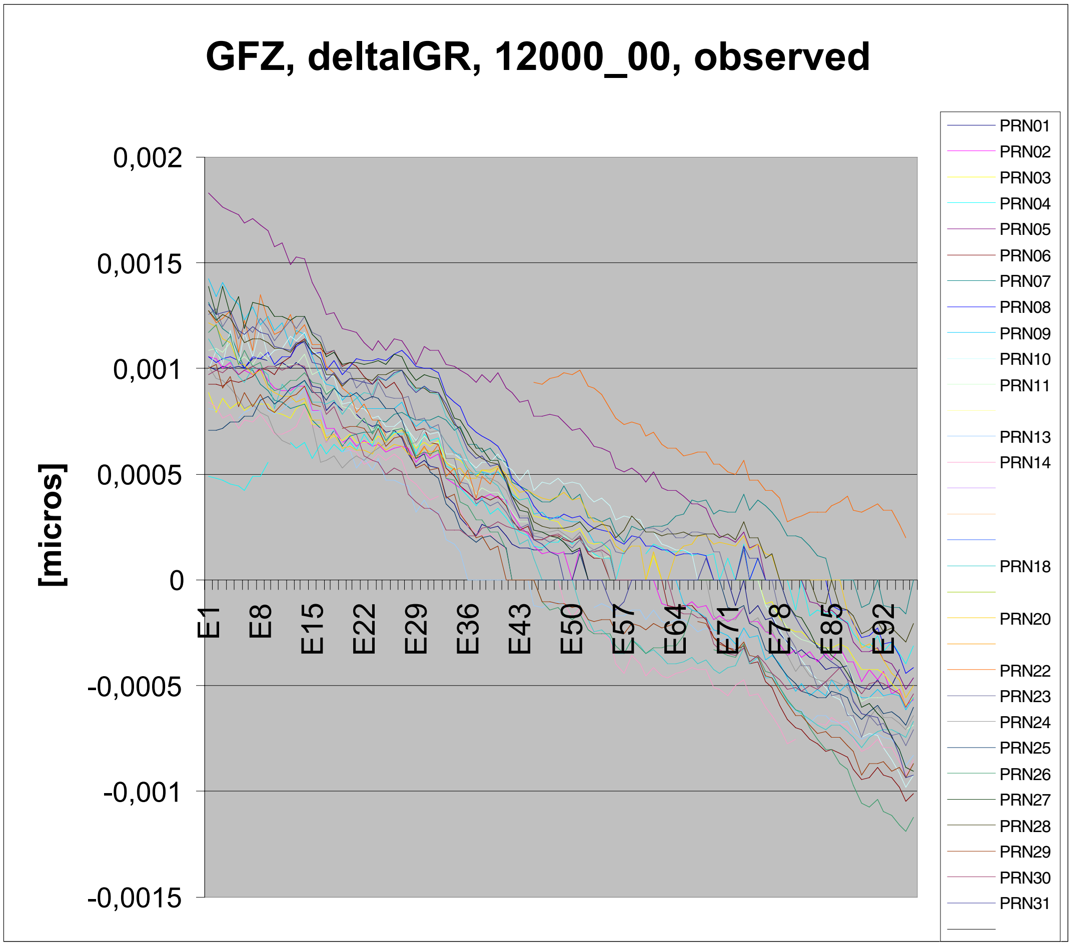

Figure 5: observed 24 hours of GFZ ultra rapid satellite clock solution w.r.t. combined IGS Rapid clocks / GPS-week 1200, day 0.

In a second step the rms of the offset and drift reduced clock differences was calculated. These differences reflect solely high order polynomial or periodical deviations.

As demonstrated in figures 5 and 6 the rms of observed satellite clocks typically range from 0.1 ns to about 0.4 ns. This result might be a little disappointing when compared to IGS Final or IGS Rapid clocks which are of a higher quality by a factor of 2-3. However, we should keep in mind that Ultra Rapid products are based on a relatively small quantity of immediately available tracking data.

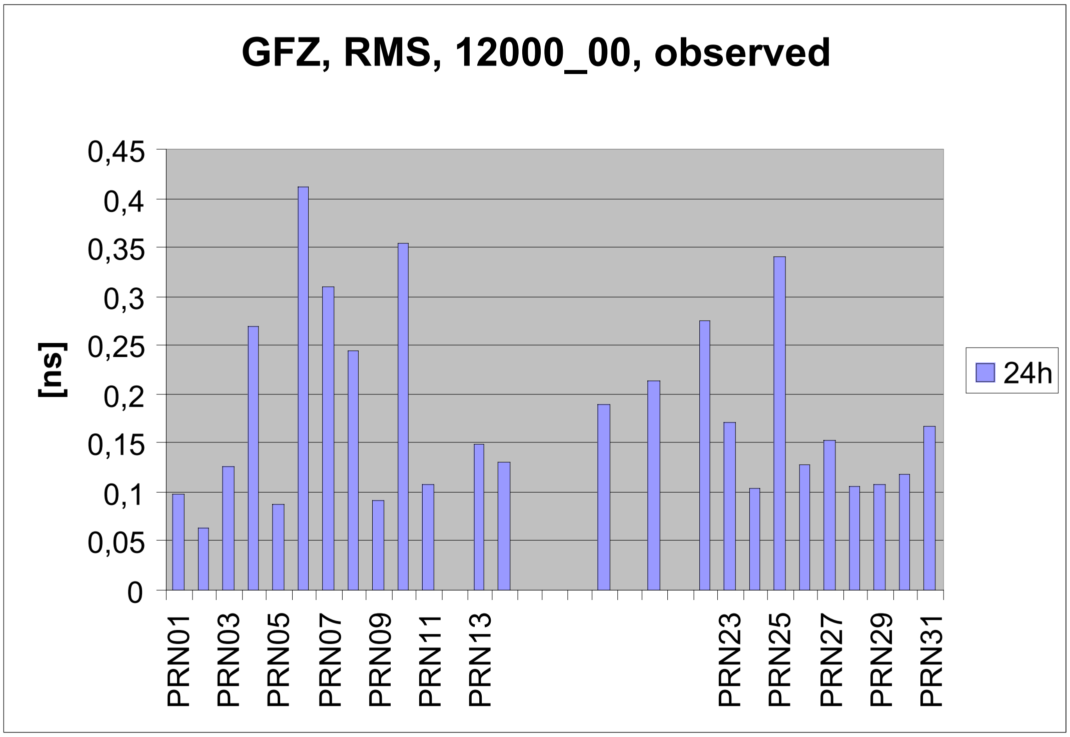

Figure 6: Satellite clock rms of GFZ observed Ultra-Rapid solution w.r.t. combined IGS Rapid clocks / GPS-week 1200, day 0.

When inspecting the 24 hours period of clock prediction we find a complete different scenario. While the clock-differences of the observed part normally populate a small band of 1-2 ns, the values within the predicted part diverge substantially (see Figure 7). Another outcome of the diagram is, that obviously some satellite clocks are more difficult to predict then others. Usually clock predictions over 12 hours are good to ±3-4 ns, depending on the stability of the satellite clock (type of clock) and the prediction model. Unfortunately extrapolations of 12 hours or more are sometimes wrong by 10 –20 ns.

For the predicted part, the clock rms is calculated in different intervals as shown in figures 8a-d. The intervals start at 0.00 GPST with the first predicted clock offset and last for 3, 6, 9, and 12 hours, respectively. Again the clock differences have been reduced for an offset and a drift in advance. As expected the rms-values increase in most cases with the length of the interval. A series of steady growing bars reflect a significant quadratic or periodic behaviour of the satellite clock. The satellite specific clock rms for the predicted interval of 3 hours is typically at the +/-1ns level growing up to +/-2 ns for the 6 hours interval. At the end of an 12 hours interval the rms of worse behaving clocks may reach +/-10ns or more. For comparison the AC-solutions from CODE, EMR, ESA and GFZ presented in figures 8a-d coincide in time but not in scale.

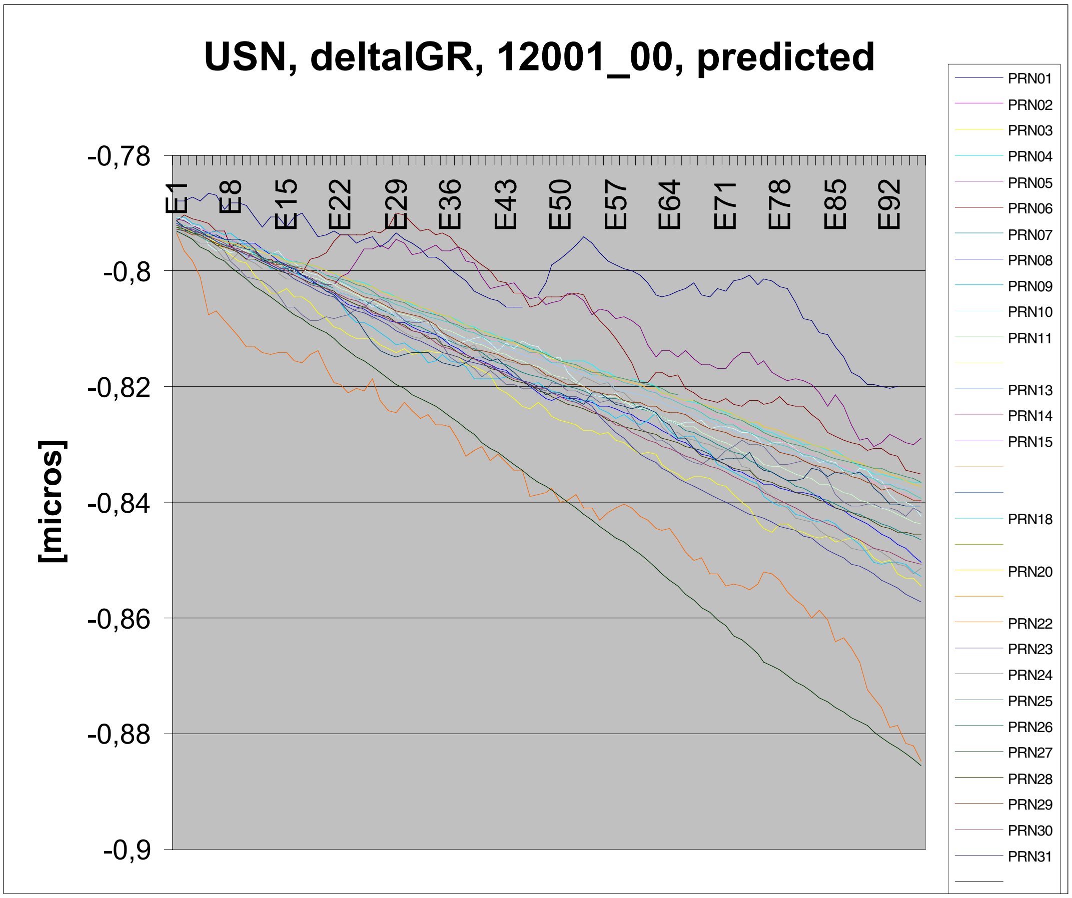

Figure 7: predicted 24 hours of USNO ultra rapid satellite clock solution w.r.t. combined IGS Rapid clocks / GPS-week 1200, day 1.

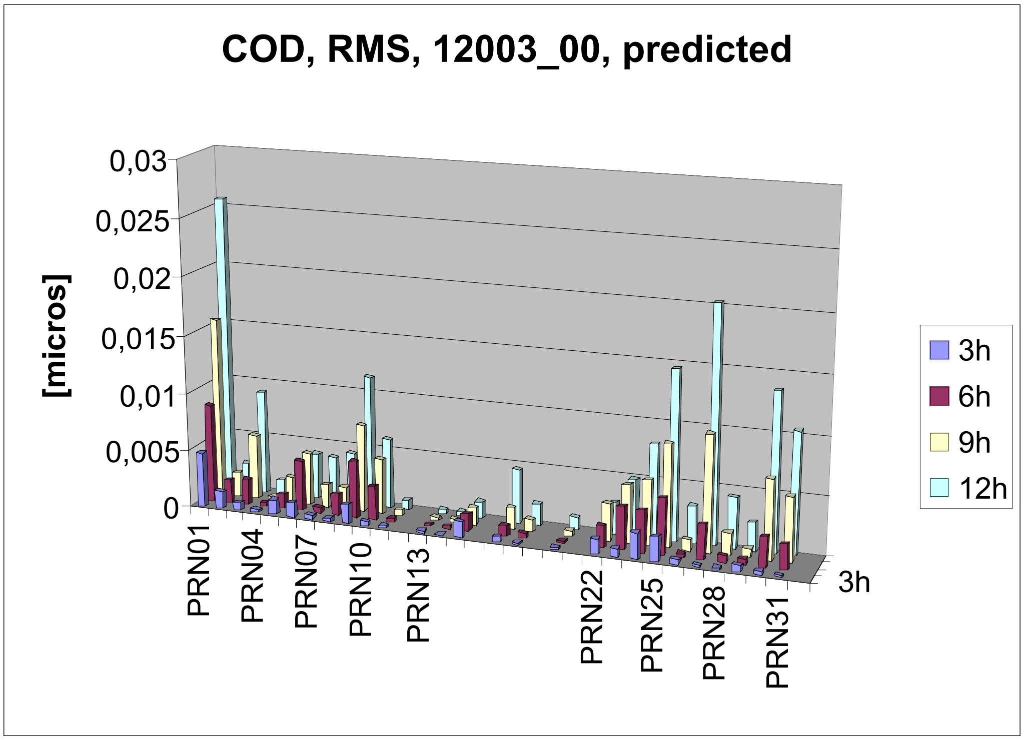

Figure 8a: Satellite clock rms of COD predicted Ultra-Rapid solution w.r.t. combined IGS Rapid clocks / GPS-week 1203, day 0.

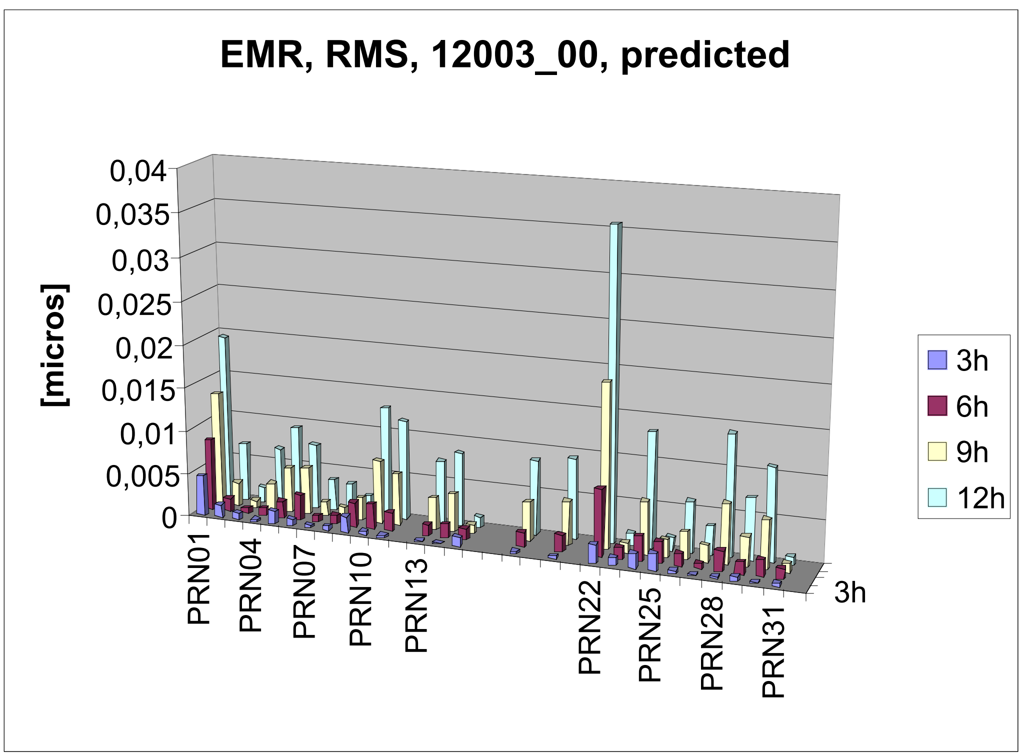

Figure 8b: Satellite clock rms of EMR predicted Ultra-Rapid solution w.r.t. combined IGS Rapid clocks / GPS-week 1203, day 0.

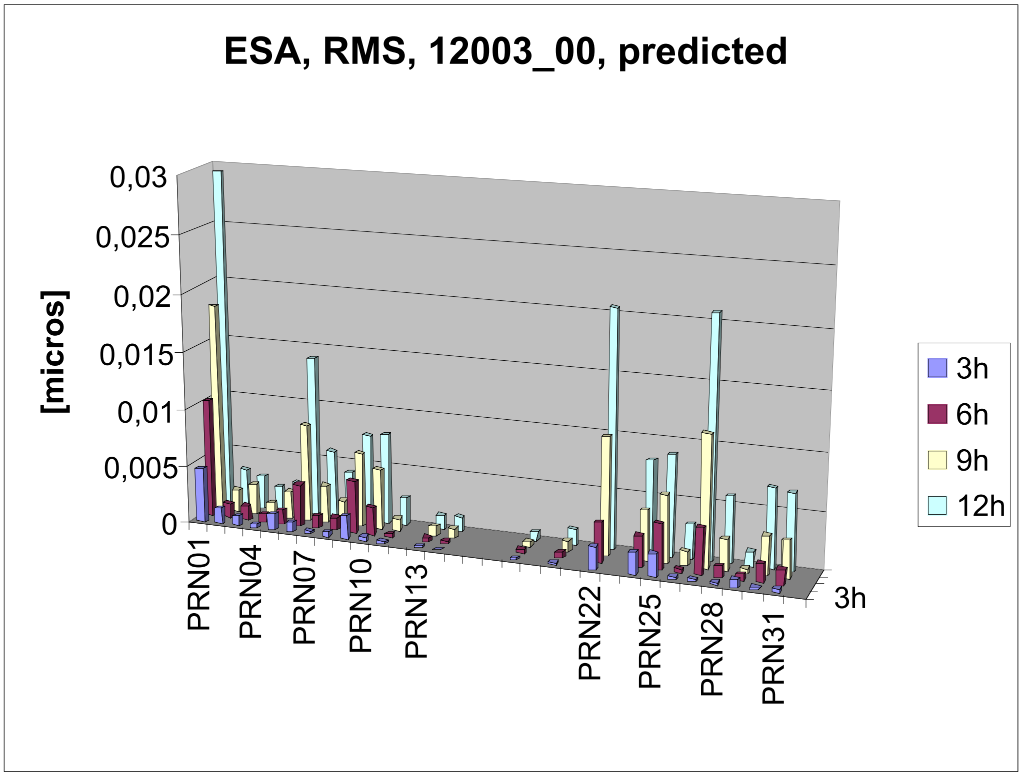

Figure 8c: Satellite clock rms of ESA predicted Ultra-Rapid solution w.r.t. combined IGS Rapid clocks / GPS-week 1203, day 0.

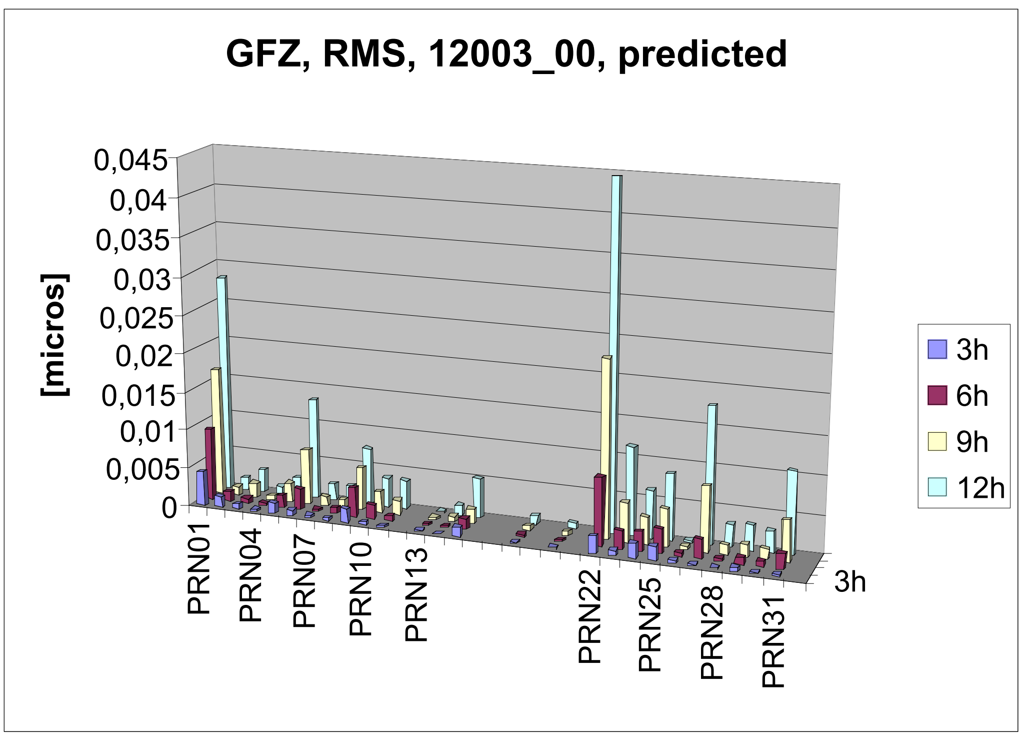

Figure 8d: Satellite clock rms of GFZ predicted Ultra-Rapid solution w.r.t. combined IGS Rapid clocks / GPS-week 1203, day 0.

The presented comparisons are carried out routinely since GPS Week 1151 (February 2002). Graphics and statistics are posted regularly at
http://www.hg.tuwien.ac.at/forschung/satellitenverfahren/igs.htm

Unfortunately the Ultra-Rapid Orbit Combination suffers frequently from a remarkable number of satellites missing in the AC – submissions (about 10-15%) due to modelling problems. The situation is illustrated in figure 9 covering the period from March 2001 until March 2002. The figure is based on ultra-rapid comparison log-files issued twice daily. Submitting 100% of the satellites would stand for submitting all tracked satellites. The scheme might be too pessimistic cause missing full submissions due to time or internet restrictions also reduce the score. On the other hand satellites which are forwarded by less than 3 centers (and are therefore rejected from the combination) increase the score of the submitting AC. Within the period March 2001-March 2002 about 85% of the tracked satellites passed the combination (about 3-4 missing satellites (out of 28) per IGU update). In the second half of 2002 the situation improved and the number of satellites excluded in the IGU orbits went down to 1-2 satellites per submission. The average percentage of satellites provided in the IGU-orbits with an accuracy better than 20cm could be enhanced to over 90% end of 2002. Satellite orbits with reduced accuracy were still rejected from the combination.

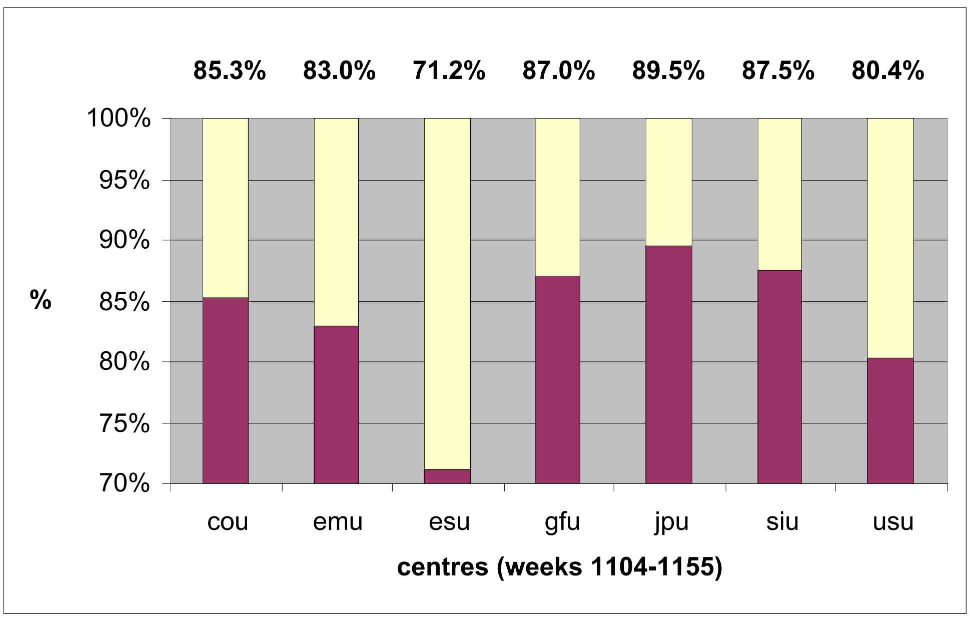

Figure 9: Percentage of satellites submitted within the AC's Ultra Rapid Orbit File (March 2001 until March 2002)

In April 2002 the IGS Analysis and Network Workshop 'Towards Real Time' took place in Ottawa. A number of recommendations were passed aiming at short- and medium-term improvements of the IGS products. Concerning the Ultra Rapid Products it is envisaged to shorten the prediction periods and thus to improve the orbit and clock quality significantly due to more frequent updates (e.g. 3 or 6 hourly updates). A more comprehensive report of this successful meeting comprising the official list of workshop recommendations has been made available via http://igscb.jpl.nasa.gov/mail/igsmail/2002/msg00183.html .

SP3- Format Update

It has been demonstrated that the old SP3 standard format for exchange of satellite orbits and clock corrections lacks of flexibility e.g. to characterize sufficiently the variable accuracy of the given data points within the IGU-orbits or to discriminate between observed and predicted data points. Therefore a new format update, labelled SP3c, has been developed under the direction of Steve Hilla from NGS (Hilla, 2003). Data exchange in SP3c format among AC's started on Dec,1st, 2002, the start of distribution of IGS Combined SP3c files will be early in 2003. A comprehensive description of the new format can be obtained via ftp://igscb.jpl.nasa.gov/igscb/data/format/sp3c.txt .

Summary and Outlook

Early in 2003 Gerd Gendt from GFZ Potsdam started his term as the new IGS Analysis Coordinator. Within a few months the IGS combination software package has been successfully installed at GFZ Potsdam. Although some Analysis problems could be solved in 2002 there are still a number of open questions to tackle.

So future activities will certainly focus on

- the implementation of more frequent updates of IGS Near Realtime products (IGU's)
- the real time dissemination of IGS data and products
- the implementation of the new IAU 2000 Resolutions comprising an updated nutation and precession model as well as the paradigm of the non rotating origin
- the implementation of new IERS Conventions,
  (e.g. subdaily ERP model, see Kouba, 2003a)
- the adoption of a new realigned (UTC) clock time scale
- the full integration of GLONASS data and products within the IGS product lines
- the stabilization of the varying IGS TRF scale e.g. by introducing new antenna calibrations
- the delivery of a really unconstrained GNSS 'technique-specific' combined coordinate solution to IERS

Finally, I want to wish the new IGS ACC Gerd Gendt and his team all the best for the upcoming years.

Acknowledgements

I want thank all people within the IGS and all components of the IGS for their support and cooperation over the past two years. My special thanks have to go to Remi Ferland, Jim Ray and Jan Kouba for a large number of email-discussions and their invaluable scientific support in questions concerning the reference frame and the clock products. Moreover I have to thank the CODE IGS team in Berne, in special Urs Hugentobler, Stefan Schaer and Rolf Dach, for a lot of discussions concerning improvements in the combination software, for maintaining the operating system and for looking after the combination during a huge number of weekends.

Moreover the author wishes to thank Veronika Bröderbauer for the preparation of the Ultra-Rapid Clock Comparisons and for the maintenance of the related Web-Site. Last but not least, I am very much indebted to my colleague, Elisabeth Fragner for her invaluable help. During the past two years she spent countless hours at my side in operating the IGS product combination software.

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Reference Frame Working Group Technical Report

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Abstract

Natural Resources Canada's (NRCan) Geodetic Survey Division (GSD), on behalf of the International GPS Service (IGS) and its Reference Frame Working Group, combines a consistent set of station coordinates, velocities, Earth Rotation Parameters (ERP) and apparent geocenter to produce the IGS official station position/ERP solutions in the Software Independent Exchange (SINEX) format. The weekly combination includes solutions from the Analysis Centers (AC), while the Global Networks Associate Analysis Centers (GNAAC) provide quality control.

The weekly AC solutions include estimates of weekly station coordinates and daily ERPs. The ACs currently process weekly data from between 40 and 140 stations They also provide separately, satellite orbit and clock estimates as part of their daily products, which are independently but consistently combined by the IGS AC Coordinator to produce the IGS orbit/clock products. The weekly combined station coordinates are accumulated in a cumulative solution containing estimated station coordinates and velocities at a reference epoch.

This year activities also included the implementation of the IGS realization of ITRF2000. All the proposed additions/changes are in the Southern Hemisphere, with the main objective being to improve the reference frame (RF) station distribution. In South America, two new stations were added while two old ones were removed. Three other stations were also added; one on Ascension Island in the Atlantic Ocean, one on Diego Garcia Island in the Indian Ocean and one in Australia.

The group also participated to two IERS activities; namely, the definition of the SINEX version 2.0 and some analysis of the stability of ERP's. The objectives of the SINEX version 2.0 extensions were to accommodate the requirements of other techniques and the inclusion of the normal equations for multi-techniques combinations.

Introduction

Station coordinates and velocities, Earth Rotation Parameters (ERP) and geocenter products are generated within the Reference Frame Working Group (RFWG) (Kouba et. al., 1998). These products also influence the combination of the GPS satellite ephemeredes and clock products. Since February 27, 2000 (GPS Week 1051), the AC coordinator aligns the orbit products to the weekly SINEX cumulative combinations, thus ensuring IGS products consistency. The weekly

SINEX combination is available within 12 days (Thursday) of the end of each GPS week. The ERPs are included in the weekly SINEX combination along with the station coordinates. The combination uses all the available covariance information.

The IGS RFWG contribution to the International Terrestrial Reference Frame (ITRF) can be subdivided into two main initiatives: first, the participation of ACs and IGS in the ITRF solutions and second, the realization and dissemination of ITRF. The IGS RFWG contribution to ITRF2000 was provided in November 2000 and included 167 stations (Ferland, R. 2002). For the period of GPS weeks 0837 (January 21, 1996) and 0977 (October 3, 1998), the weekly combined solutions from JPL, MIT and NCL Global Associates Analysis Centers (GNAAC) were used in the cumulative solution. Since GPS week 0978 (October 4, 1998), the seven ACs (COD, EMR, ESA, GFZ, JPL, NGS and SIO) are used in the combination, while the GNAACs are used to control the quality of the weekly combination (Table 1). The IGS contribution took the form of a cumulative solution that included data between GPS weeks 0837 and 1088 (January 21, 1996 – November 18, 2000). The IGS realization of ITRF is accomplished with a subset of stations of the IGS network. For the realization of ITRF2000, 54 high quality stations were selected. (Kouba et al., 1998). The accessibility to the reference frame is facilitated through the combined “IGS core products” of station coordinates, the Earth Rotation Parameters and/or the precise orbits, and the satellites/stations clock solutions. The IGS Reference frame realization of ITRF can be accessed, by GPS users, with their precise code and phase observations. Data used to realize an IGS ITRF will also be subsequently contributed to the IERS combination process to generate ITRF at future epochs.

Table 1. IGS Analysis and Associate Analysis Centers

IGS Analysis Centers (AC)	
CODE	Center for Orbit Determination in Europe, AIUB, Switzerland
ESOC	European Space Operations Center, ESA, Germany
GFZ	GeoForschungsZentrum, Germany
JPL	Jet Propulsion Laboratory, USA
NOAA	National Oceanic and Atmospheric Administration / NGS, USA
NRCan	Natural Resources Canada, Canada
SIO	Scripps Institution of Oceanography, USA
IGS Global Network Associate Analysis Centers (GNAAC)	
NCL	University of Newcastle-upon-Tyne
MIT	Massachusetts Institute of Technology
JPL	FLINN Analysis Center Jet Propulsion Laboratory (up to 00/09/09)

Weekly SINEX combination

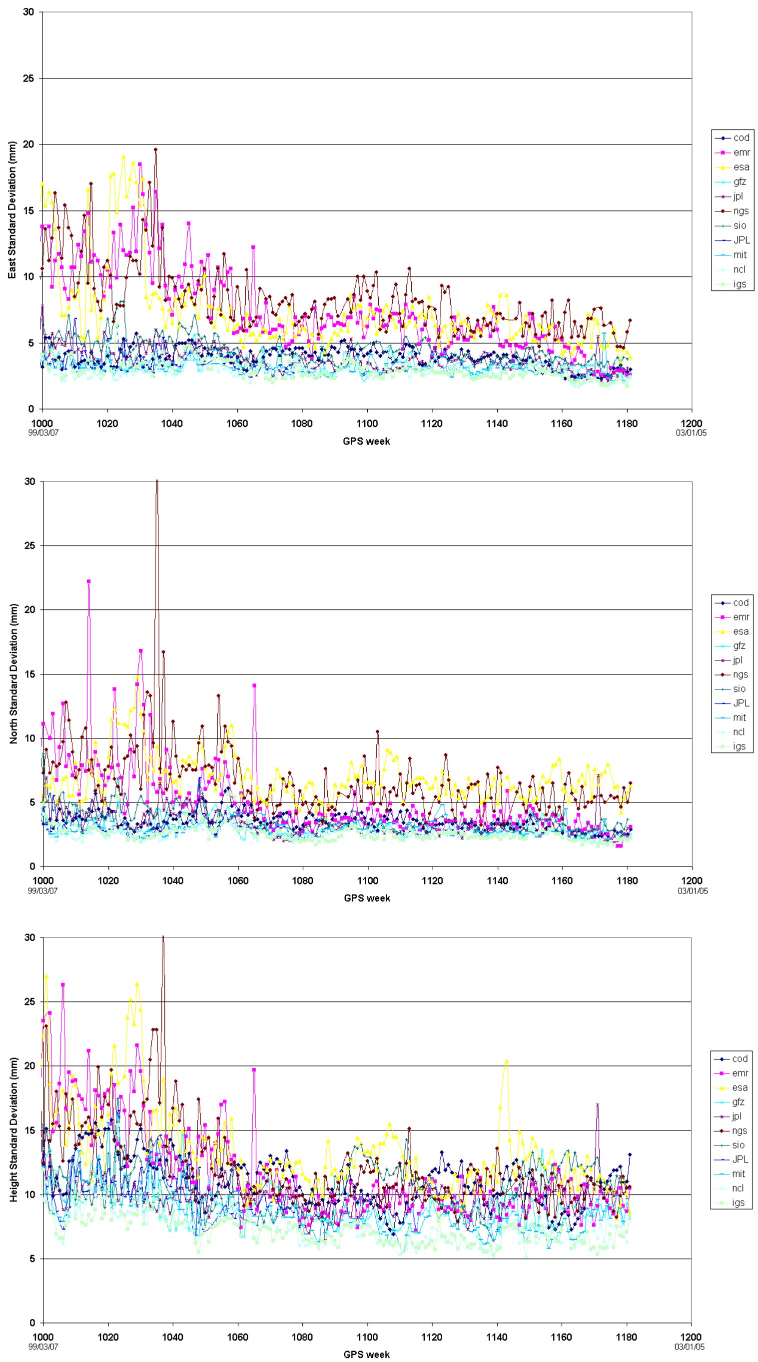

Figure 1. North, east and height stations residuals standard deviation between the AC, GNAAC and IGS weekly solutions and the IGS cumulative solution.

The AC solutions are combined using the least-squares technique. All the available covariance information between the station coordinates within each AC solution is used. Since GPS week 1013 (June 6, 1999) the weekly combination also includes daily ERP (pole position and rate, calibrated length of day (Mireault et al. 1999)) and since GPS week 0978 (October 4, 1998) weekly apparent geocenter estimates. The cumulative combination is updated every week with the latest weekly combination. The alignment of the weekly and cumulative solution is done using a set of reference frame stations (see the next section). Since GPS week 1000 (March 7, 1999), weekly comparisons between the IGS weekly and the cumulative solution show standard deviations of about 3 mm horizontally and 6-8 mm vertically. Figure 1 shows the standard deviation of the weekly station coordinates residuals between the ACs GNAACs and IGS with respect to the IGS cumulative solution. Gradual improvement is apparent especially in the height component. The bandwidth of the deviations is also decreasing, indicating a better level of agreement between the various solutions.

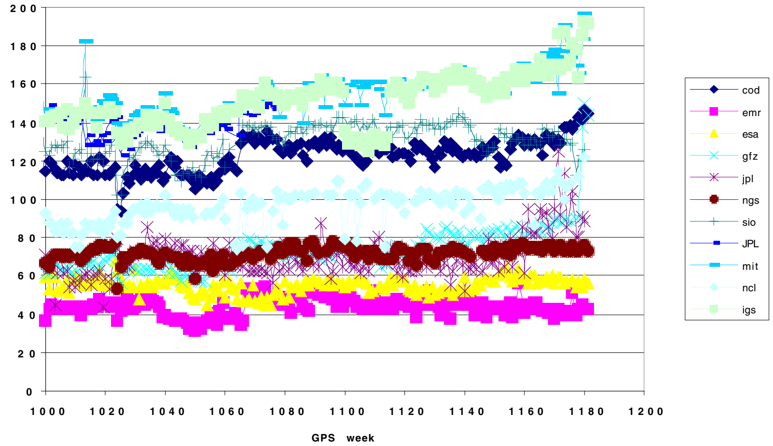

Figure 2. Number of Stations in the Weekly AC, GNAAC & IGS SINEX Solutions

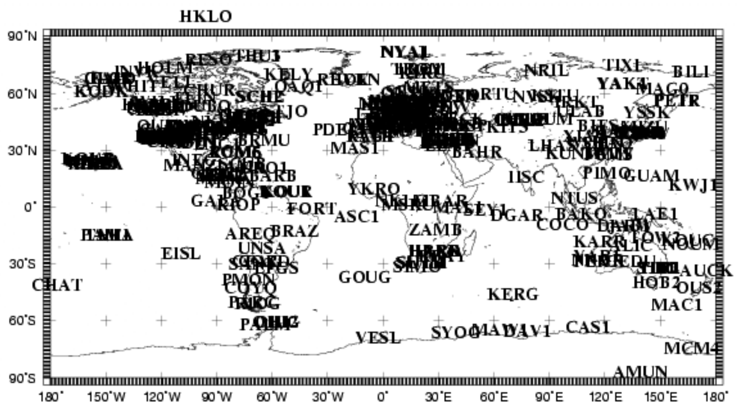

Figure 3. Stations in the "extended" Cumulative Solution

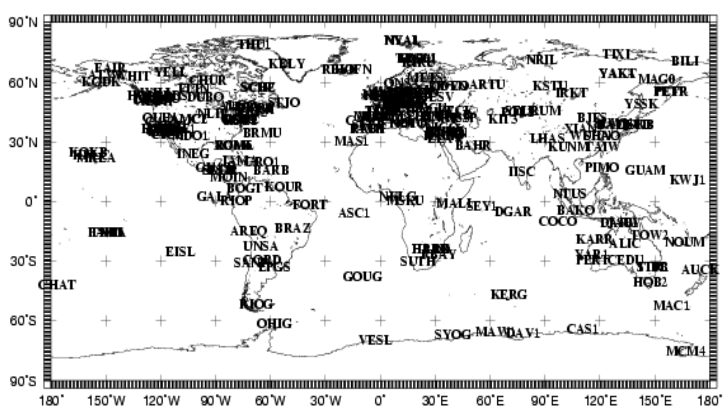

Figure 4. Stations available in the Cumulative Solution

Equipment, local environment and processing changes are the causes for a number of discontinuities in the station coordinate time series. Those are also visible in the residual time series after linear. Comparisons done in the past between the weekly and cumulative solution statistics have indicated that non-random effects account for up to 30% of the residuals signature. Discontinuities, which tend to affect mainly the height, are generally caused by either blunders, equipment or processing changes.

The number of operational stations is steadily increasing. The number of stations processed and submitted by the ACs is also increasing. In the IGS weekly combination, the number of stations increases on average by one station per month. Due to ongoing changes in the stations selected by the ACs in their processing, the number of stations in the cumulative solution increases at rate of almost two stations per month. Figure 2 shows the evolution in the number of stations included in the weekly ACs, GNAACs and IGS combined SINEX solutions. The ACs currently process about 40 and 140 stations weekly.

The weekly combined solution now exceeds 180 stations. All the weekly station coordinate estimates provided by the AC are currently combined and made available. The "extended" cumulative solution generated from these weekly combinations currently includes over 340 stations (Figure 3). Of those, 215 stations with reliable information are included in the IGS SINEX Combination (Figure 4). Cumulative solutions for over 120 stations are not yet releases for the following reasons: they are missing essential info such as dome #, site logs; they cover a short time span (e.g. < ~1 year) which prevent reliable velocity estimation; or they are located in geographical areas that are already well covered (e.g. North America and Europe).

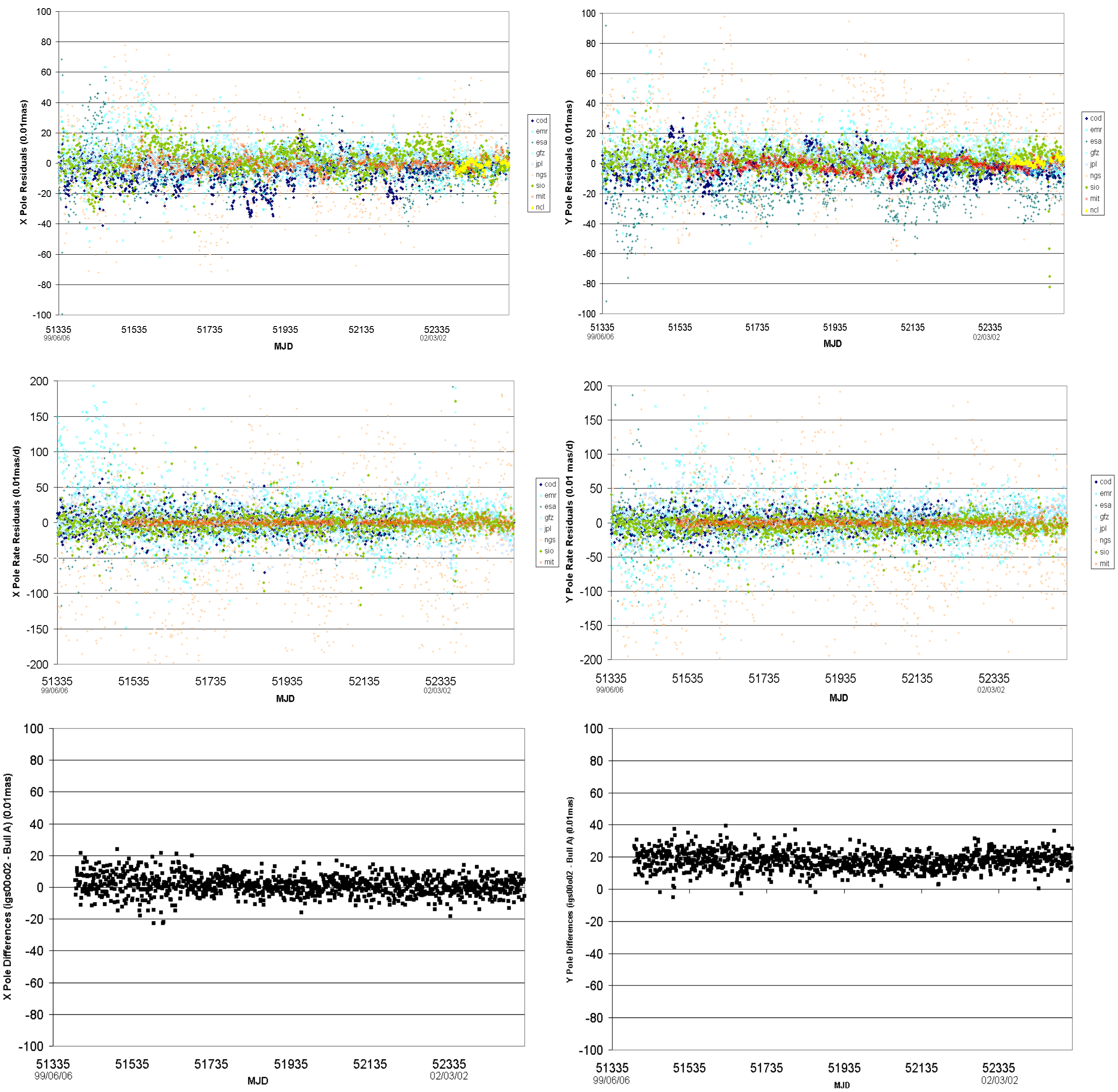

Figure 5. Daily X Pole, Y Pole (top), X Pole Rate, Y Pole Rate (middle) differences between the combined solution "igs00p02" and the AC & GNAAC estimates. Daily X Pole, Y Pole (bottom) differences between the combined solution "igs00p02" and the Bulletin A.

The daily ERPs are combined in the weekly SINEX solution along with the station coordinates by making use of all covariance information. The best AC pole positions and rates are consistent at the 0.05-0.10mas (0.10–0.20mas/d), while the calibrated LOD are consistent at 20-30us. Figure 5 show the daily residuals time series for the X and Y pole (Top) and their rates (Middle) between the combined solution “igs00p02” and the AC/GNAAC. The bottom portion shows the daily difference between the combined solution and Bulletin A. Note that the IGS combined solution and the Bulletin A are not independent, since the AC solutions contribute significantly to Bulletin A. The Bulletin A daily estimates were linearly interpolated to match the corresponding epochs of the IGS combined values. Small differences between the AC combined pole and pole rates are due to differences in processing strategy (e.g.: different weighting and rejection criterion). Independent daily ERPs using a different weighting are also estimated as part of the final GPS orbit combination process “igs95p02”. Comparison between the igs00p02 and igs95p02 show no significant average difference between them, and a noise level of about 0.06mas (0.10mas/d) which is similar to the differences with respect to Bulletin A (bias removed) (0.07mas & 0.17mas/d). The GNAAC NCL analysis center has also started combining the pole positions as well as the LOD.

Implementation of ITRF2000

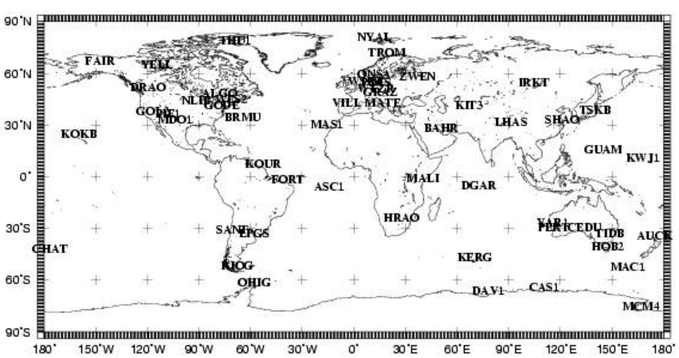

Figure 6. IGS00 Reference Frame Stations

ITRF2000 (Altamimi, 2001) was made available in the spring of 2001. The ITRF2000 combines solutions from a number of space techniques including Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Doppler Orbitography by Radio-positioning Integrated on Satellite (DORIS) and GPS. The IGS solution was part of a group of about 20 global solutions used for the realization of ITRF2000. Five other GPS (AC) global solutions were also submitted as well as six densification solutions. The IGS cumulative solution submitted to ITRF, was an edited solution extracted from IGS00P46.snx. The solution included the GPS weeks 0837 to 1088. The ACs/GNAACs (COD, GFZ, JPL, NGS, NCL) also provided their global cumulative solutions that are also included in ITRF2000. The "IGS00" realization of ITRF2000 was extracted from the cumulative solution "IGS01P37.snx" GPS week 1131 (September 9-15, 2001). After an analysis of the performance of the reference frame stations used for IGS97, it was decided to remove two stations and add five new ones. The station BRAZ was removed because it had been providing timely data for only a few weeks during the previous 12 months. Station AREQ was removed due to an earthquake that caused a significant discontinuity on June 23, 2001 ($\Delta\varphi$= -34cm, $\Delta\lambda$ = -47cm, Δh= - 2cm). In an attempt to compensate for removal of BRAZ and AREQ from the reference frame stations list, stations LPGS and RIOG, both in Argentina, were added. Both stations were contributing quality and timely data; their coordinates time series were also stable. RIOG was also collocated with DORIS. Stations at ASC1 (Ascension Island) and DGAR (Diego Garcia Island) were also added. These stations are also contributing to strengthen the reference frame network around Africa. Alternatives on the African continent were considered (e. g.: NKLG& YKRO), but, their track record was considered too short for reliable velocity estimate. One more station (CEDU) was added in Australia. See Figure 6 for a map of the IGS00 Reference Frame stations.

Table 2. Transformation Parameters from IGS (ITRF97) to IGS (ITRF2000) at December 02, 2001

At Dec 02, 2001	Translations			Rotations			Scale
	TX (mm)	TY (mm)	TZ (mm)	RX (mas)	RY (mas)	RZ (mas)	S (ppb)
(1 sigma)	-4.5 (4.1)	-2.4 (5.0)	26.0 (7.5)	-0.024 (0.092)	-0.004 (0.099)	-0.159 (0.076)	-1.451 (0.27)
Rate (/y) (1 sigma)	0.4 (1.7)	0.8 (1.9)	1.6 (2.8)	0.003 (0.038)	-0.001 (0.040)	-0.030 (0.034)	-0.03 (0.12)

Although, the ITRF97 and ITRF2000 are supposed to be aligned, there are some small transformation parameters between their IGS realizations mainly due to network effects. Based on the 49 common stations between the two IGS realizations of ITRF, the estimated transformation parameters (3 translations, 3 rotations, 1 scale and their respective rates) from IGS (ITRF97) to IGS (ITRF2000) are given in Table 2. The change from IGS97 to IGS00 was made on GPS week 1143 (December 2, 2001).

As part of an IERS analysis campaign, several strategies to realize ITRF2000 were analyzed to evaluate their effects on the ERP's. The strategies included different sub-networks and weighting schemes. The strategies were tested on two years of IGS weekly SINEX combinations. Comparisons have shown that the impact of the different strategies on the ERP's never exceeded 0.03 mas.

The differences between the ITRF2000 and IGS00 reference frame stations have position RMS of (0.5mm, 0.7mm, 2.5mm) and velocity RMS of (0.6mm/y, 0.8mm/y, 1.7mm/y) in the north, east and height directions.

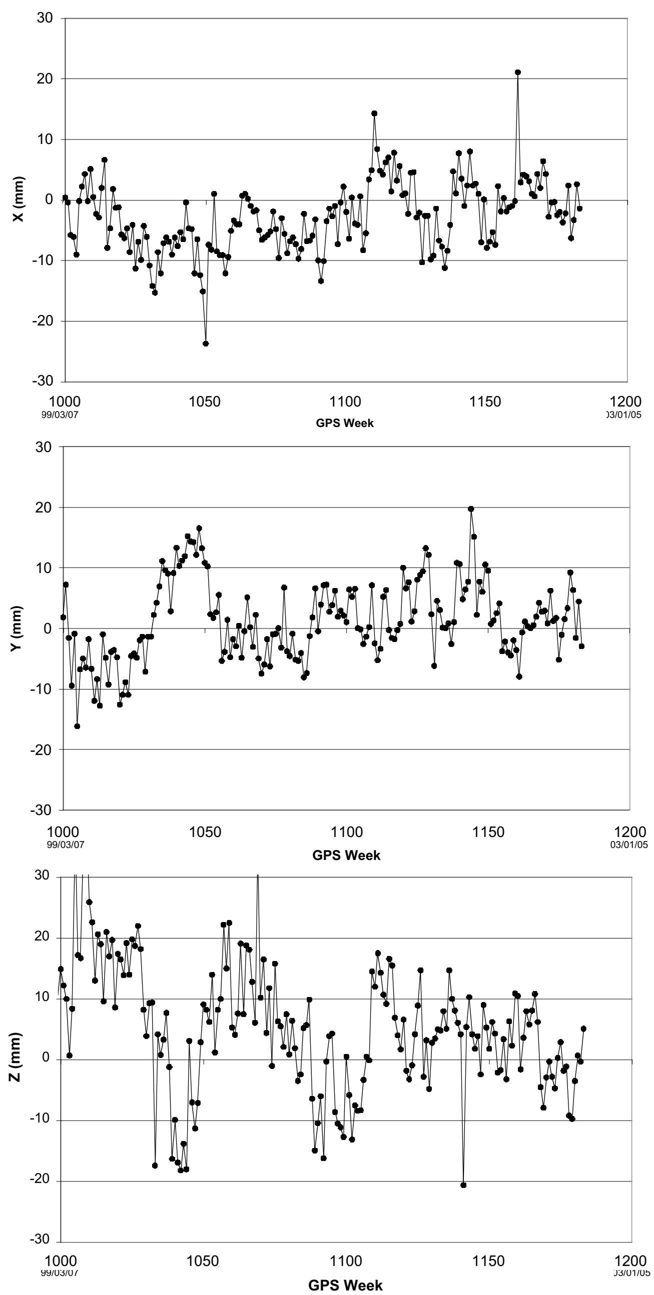

Figure 7. Apparent Geocenter Weekly estimates with respect to current IGS realization of ITRF2000.

Figure 7 shows the weekly apparent geocenter position. Linear regression analysis on those time series indicates that there may still be some small drift in all 3 components of the apparent geocenter (2.0 +-0.8 mm/y, 1.5 +- 0.9mm/y, -3.7 +- 1.4 mm/y).

Summary

The IGS cumulative solution now contains about 340 stations among which 215 are made available weekly. This is considered sufficient for ITRF densification purposes. The IGS realization of ITRF uses a subset of the IGS cumulative solution. This improves the internal stability and consistency of the weekly product alignment. Tests with different realizations of ITRF2000 have indicated that the effect on the ERP's never exceeded 0.03mas. The use of the 7 ACs and the 2 GNAACs provide significant redundancy and robustness to the analysis. The analysis has also shown that station statistics have a gradually improved over the years. The weekly apparent geocenter estimates show improved agreement with the IGS realization of ITRF2000 origin compared to the IGS realization of ITRF97.

Acknowledgements

A large number of agencies contribute to IGS. Among them are the agencies responsible for the installation and maintenance of the tracking stations, the regional and global data centers in addition to the ACs and GNAACs already mentioned. A complete list of contributors can be found at the IGS web site (http://igscb.jpl.nasa.gov/). Also thanks to J. Kouba and P. Heroux for reviewing this report.

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Time Series Combination of Station Positions and Earth Orientation Parameters

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Abstract

CATREF software developed to generate ITRF solutions was enhanced in order to rigorously combine station positions (and velocities) together with Earth Orientation Parameters (EOP). It is also well adapted for time series combination of station positions and EOP's. We present in this paper some comparative analysis of available time series solutions provided in SINEX format from 4 techniques: VLBI, SLR, GPS and DORIS.

Introduction

Up to now, the ITRF, ICRF and EOP are determined separately and consequently their consistency is difficult to assess. Since some 5 years ago, several analysis/technique centers started to make available time series of daily/weakly/monthly solutions of station positions and daily EOP provided in SINEX files. Time series combination becomes interesting since it allows, in particular, detecting and monitoring all kind of variations and discontinuities in station positions. Moreover, the inclusion of EOPs in the ITRF combination allows to improve consistency between IERS products.

Combination model

The initial model implemented in CATREF software allows simultaneous combination of station positions and velocities. A large description could be found in (Altamimi et al. 2002). Assuming that for each individual solution *s*, and each point *i*, we have position X_s^i at epoch t_s^i and velocity $\dot{X}_c^i$, expressed in a given TRF *k*.

The combination consists in estimating:

- Positions X_c^i at a given epoch t_0 and velocities $\dot{X}_c^i$, expressed in the combined TRF *c*,
- Transformation parameters T_k at an epoch t_k and their rates $\dot{T}_k$, from the combined TRF *c* to each individual frame *k*.

The general combination model is given by the following equation:

$$\begin{cases} X_s^i = X_c^i + (t_s^i - t_0) + T_k + D_k X_c^i + R_k X_c^i \\ \quad + (t_s^i - t_k)[\dot{T}_k + \dot{D}_k X_c^i + \dot{R}_k X_c^i] \\ \dot{X}_s^i = \dot{X}_c^i + \dot{T}_k + \dot{D}_k X_c^i + \dot{R}_k X_c^i \end{cases} \qquad (1)$$

Using pole coordinates x_s^p , y_s^p and universal time UT_s as well as their daily time derivatives $\dot{x}_s^p$, $\dot{y}_s^p$ and LOD_s, the corresponding equations are:

$$\begin{cases} x_s^p = x^p + R2_k \\ y_s^p = y^p + R1_k \\ UT_s = UT - \frac{1}{f} R3_k \\ \dot{x}_s^p = \dot{x}^p + \dot{R}2_k \\ \dot{y}_s^p = \dot{y}^p + \dot{R}1_k \\ LOD_s = LOD + \frac{\Lambda}{f} \dot{R}3_k \end{cases} \quad (2)$$

where f = 1.002737909350795 is the conversion factor of UT into sideral time. Considering LOD =, $\Lambda_0 \frac{dUT}{dt}$ is homogenous to time difference, so that Λ_0 = 1 day in time unit.

Note that the link between EOP and TRF is ensured upon the 3 rotation angles $\dot{R}1$, $\dot{R}2$, $\dot{R}3$, and their time derivatives.

In order to precisely define the datum of the combined frame minimum constraints equations were implemented in CATREF software, allowing to express the combined solution in any external frame. For more details concerning equations of minimum constraints and their practical use, see for instance Altamimi et al., (2003).

Data Analysis

Input Data

- VLBI: 24h-session sinex files over 1990-2003, provided by Goddard Space Flight Center (GSFC) VLBI Group, using the terrestrial reference frame of gsfd001 (IVS, 2003),
- SLR: weekly solutions over 1999-2002, provide by Italian Space Agency (ASI) , (Luceri, 2003),
- GPS: Official IGS weekly combined solutions over 1999-2003 (Ferland, 2003), and JPL weekly solutions over 1996-2002 available at IGS, (Heflin et al., 2003),
- DORIS: IGN-JPL weekly solutions over 1993-2003, by IGN-JPL, (Willis, 2003).

Analysis Strategy

The analysis strategy applied currently to times series combination is as follows:

- Remove original constraints and apply minimum constraints equally to all constrained solutions
- Use as they are the minimally constrained solutions

- Perform per-technique combinations (TRF + EOP), all expressed in ITRF2000 using equations of minimum constraints. At this step the per-technique combinations are obviously free from any local ties.
- Identify and reject outliers and properly handle discontinuities, using break-wise approach
- Combine the per-technique combinations adding local ties in collocation sites
- Estimate variance components and iterate as necessary.

Analysis Results

From the per technique combinations we extracted the geocenter estimates for SLR/ASI, GPS/JPL and DORIS/IGN-JPL time series as illustrated in Figure 1. These geocenter estimates are in fact weekly translation components (over the period of the available data) with respect to ITRF2000 origin, being aligned to the center of mass. While geocenter motion assessment is still a research area, we could mention that, according to Figure 1, SLR results seem to be less scattered than GPS and DORIS. Figure 1 shows also that unlike T_z component, T_x and T_y components are stable in time, with some seasonal variations. To have an idea about the magnitude of these seasonal variations, Table 1 lists the values of the annual amplitude of the geocenter components computed by:

$$dx(t) = A.\cos(2\pi f(t-t0) + \phi) \qquad (3)$$

where dx designates one of the three geocenter components: Tx, Ty, Tz. A and ϕ are annual amplitude and phase, respectively, and (f = 1) is the frequency in cycles per year. The SLR seasonal variations of the geocenter components seem to be more reliable than GPS and DORIS. Figure 1 depicts also the scale time variation for the above 3 solutions, converted in mm over the equator, showing no significant drift in time, while DORIS solution exhibit a shift of about 2 cm compared to ITRF2000. Figure 2 illustrates the daily scale variation of GSFC VLBI results, over approximately 10 years, showing less scatter from 1997 on, no significant drift and roughly zero mean with respect to ITRF2000. However we may distinguish some annual variations of about 3 mm amplitude.

Table1. Annual amplitude of geocenter components (mm)

Solution	T_x	T_y	T_z
SLR/ASI	2.2	3.6	3.2
GPS/JPL	4.1	7.2	15.8
DORIS/IGN-JPL	6.9	4.4	16.0

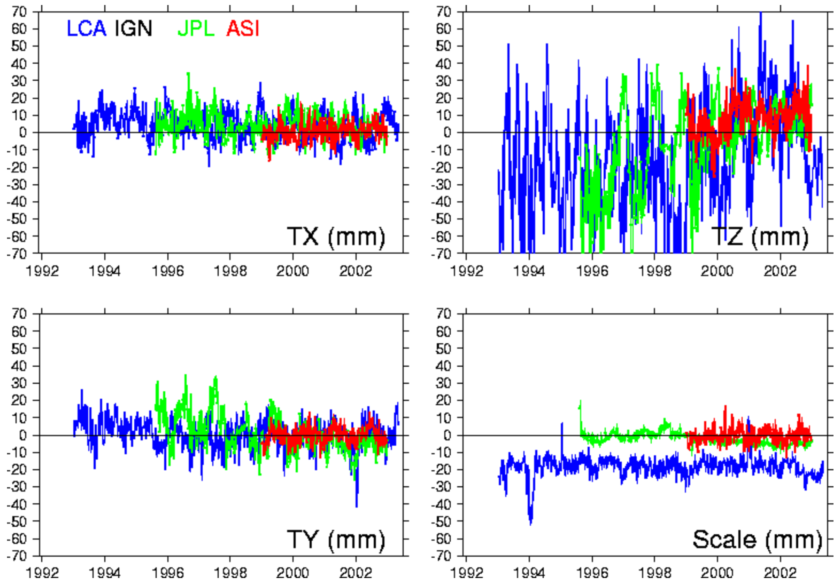

Figure 1. Origin and scale variations with respect to ITRF2000 for DORIS/IGN-JPL, GPS/JPL and SLR/ASI

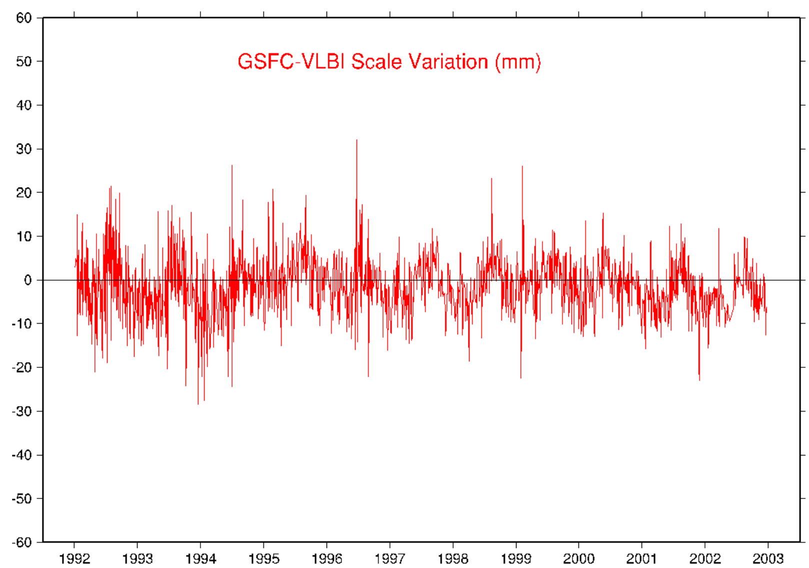

Figure 2. Daily GSFC VLBI scale variation w.r.t. ITRF2000

As results from the per technique combination, Figure 3 shows the polar motion post fit residuals (in *mas*) and Figure 4 shows the post fit residual of polar motion rates (in *mas*/yr.) and LOD (in *ms*/yr.) per technique. Moreover, Figure 5 (courtesy from D. Gambis) illustrates differences between EOP values resulted from the combination test and the IERS series C04.

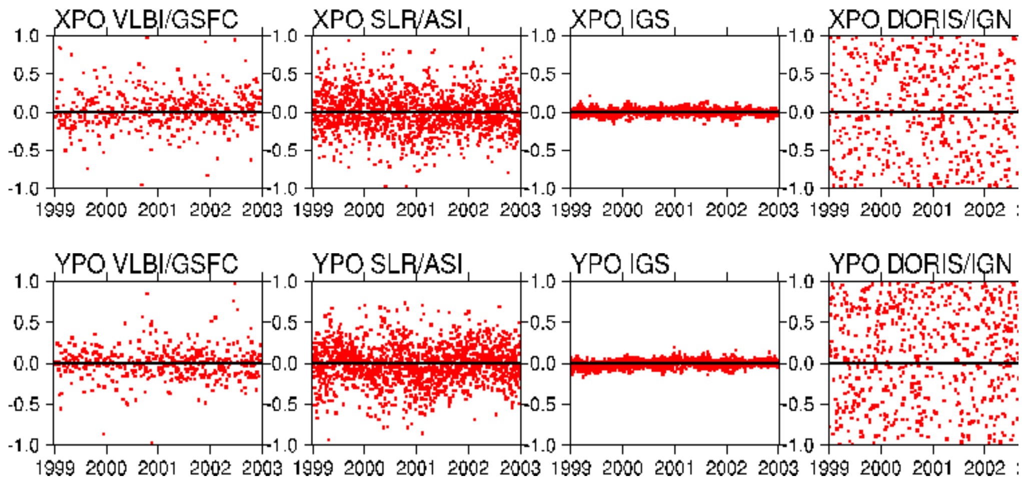

Figure 3. Post fit residual of Polar motion per technique (*mas*)

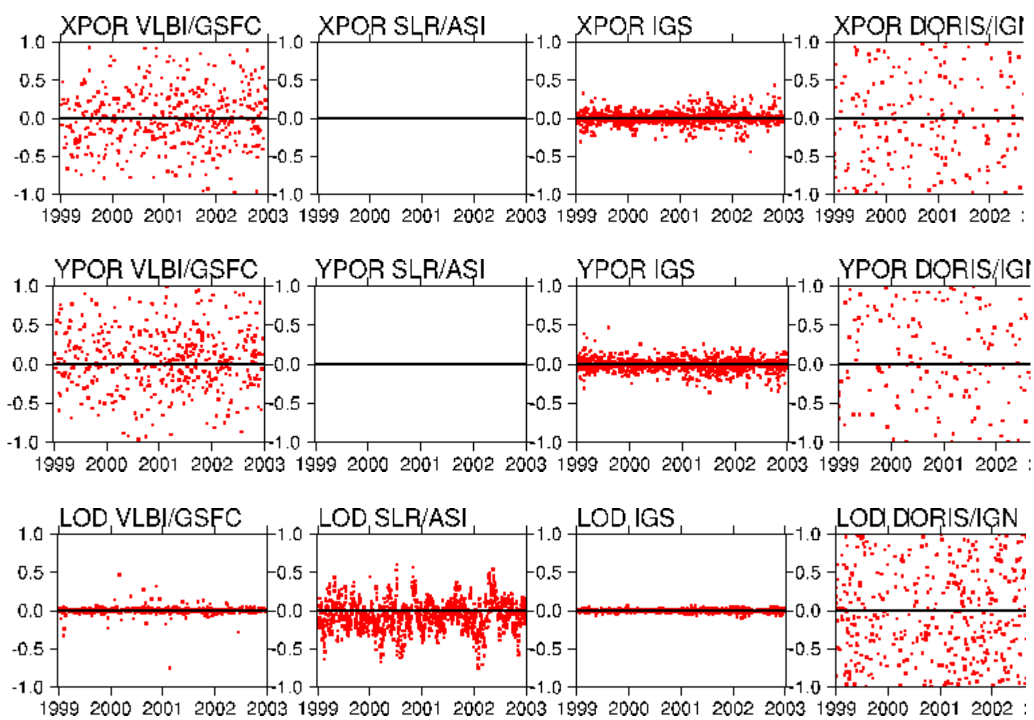

Figure 4. Post fit residual of Polar motion rates (*mas*/yr.) and LOD (*ms*/yr.) per technique

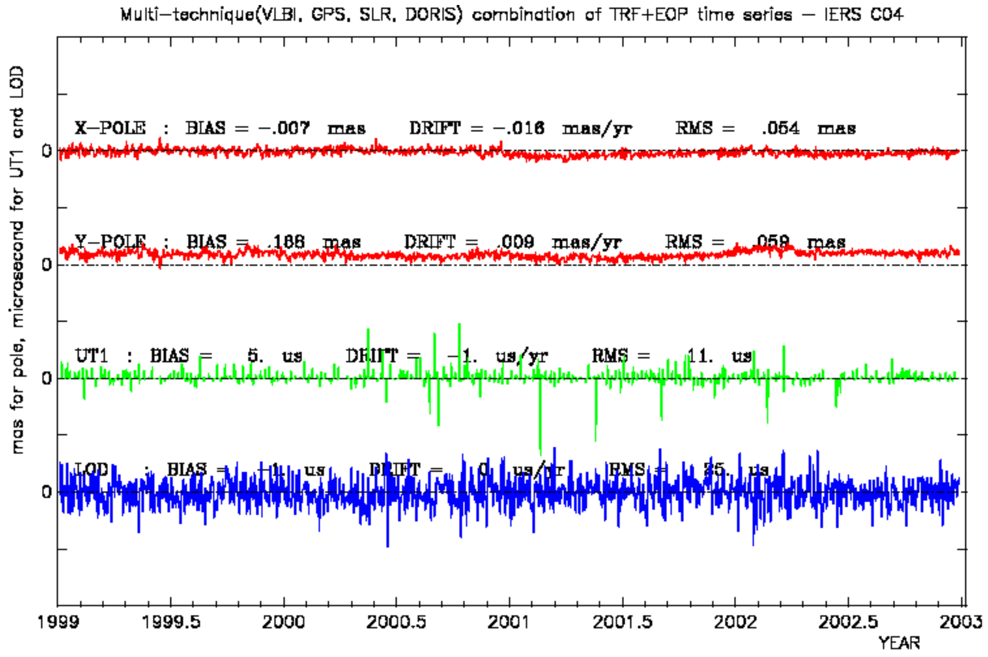

Figure 5. EOP differences with IERS C04 (*mas*) (plot courtesy from D. Gambis)

Conclusion

The EOP IGS results appear to dominate the other technique results. This is mainly due to the fact that the IGS solution is already a combination of 7 analysis centers, whereas the others are provided from one analysis center per technique. In addition, the IGS EOP estimates are based on continuous observations from more than 200 sites homogenously distributed. From Figure 5, it clearly appears that there is a bias in the y-pole component of about 170 micro-arc-second between IERS EOP series C04 and ITRF2000.

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