Reference Frame Working Group Technical Report

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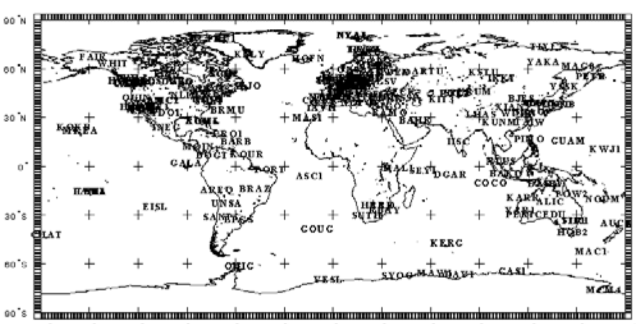
ABSTRACT

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 Associates Analysis Centers (GNAAC) provides quality control.

The weekly AC solutions include estimates of weekly station coordinates, apparent geocenter positions and daily ERPs. The ACs 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. All the AC products are required to be in a consistent reference frame. The combination of station coordinates originating from different ACs involves removing all available constraints and re-scaling the covariance information. The weekly combined station coordinates are accumulated in a cumulative solution containing estimated station coordinates and velocities at a reference epoch.



Stations in the Cumulative Solution
Figure 1

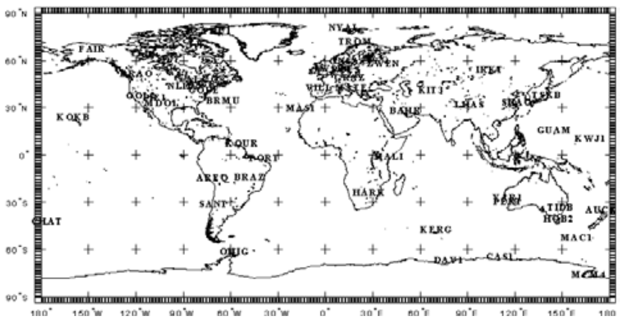
The weekly combination generally includes estimates of coordinates for 120 to 140 globally distributed stations. While the cumulative solution currently includes approximately 250 stations, about 180 (Figure 1) of them have complete information and reliable velocity estimates. The IGS combined products are required to be consistent with the most recent realization of ITRF (currently ITRF97 (Boucher et al., 1997)). This is done by transforming the weekly and cumulative solutions, respectively using 7 and 14 Helmert transformation parameters (3 translations, 3 rotations, 1 scale and their respective rates). The transformation parameters are determined from a subset of 51 high quality, globally distributed and collocated (with other space techniques) stations, also known as Reference Frame (RF) stations.

Since the beginning of 1996, weekly comparisons with ITRF97 show an accuracy of 3-4 mm horizontally and 10-12 mm vertically. Gradual improvements are apparent. Various non-random effects

are present in the station coordinates time series residuals, such as periodicities and discontinuities. Equipment, local environment and processing changes are the causes for a number of discontinuities.

INTRODUCTION

The IGS contribution to 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 contribution to ITRF2000 consisted essentially in a cumulative solution that included data between GPS weeks 0837 and 1088 (96/01/21 – 00/11/18). The solution involved 167 stations distributed as shown above in Figure 1. The ITRF realization is accomplished with a station subset of the IGS network. For the realization of ITRF97, 51 high quality stations were selected (Figure 2) (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 the precise code and phase observations. The IGS participation (IGS stations) and the IGS realization aspects are very closely related. Data used to realize an IGS ITRF will also be subsequently contributed to the IERS combination process to generate ITRF at future epochs.



IGS stations used to realize ITRF97
Figure 2

IGS PARTICIPATION TO ITRF2000

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.

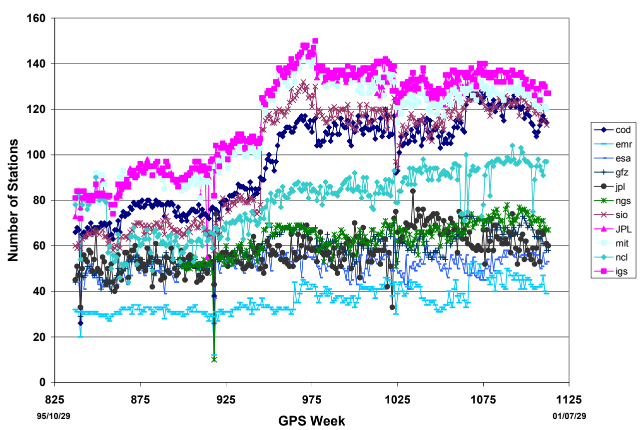
Between GPS weeks 0837 (96/01/21) and 0977 (98/10/03), the weekly combined solutions from JPL, MIT and NCL Global Associates Analysis Centers (GNAAC) were used in the cumulative solution. Since GPS week 0978 (98/10/04), the seven Analysis Centers (AC) (CODE, ESA, GFZ, JPL, NGS NRCan and SIO) are used in the combination, while the GNAAC are used to quality control the weekly combination (Table 1).

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 (99/06/06) the weekly combination also includes daily ERP (pole position and rate, calibrated length of day (Mireault et al. 1999)) and since GPS week 0978 (98/10/04) weekly apparent geocenter estimates. The cumulative combination is updated every week with the latest weekly combination. This cumulative solution includes station coordinates and velocities for about 250 sites. Of those, about 180 have reliable velocity estimate. The cumulative solution is currently aligned to ITRF97 by applying a 14-parameter transformation estimated using the set of 51 RF stations. Inner constraints in origin, orientation and scale (and their rates) are applied to the solution. Due to the large number of input solutions used and the variety of sources, there are some concerns for potential numerical instabilities; but, at this time, they appear to be that under control.

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

IGS Analysis and Associate Analysis Centers
Table 1

The number of stations contributing to weekly SINEX solutions has increased steadily since the beginning of IGS. The number of stations has gone from 25 to 60 stations in 1996 to between 40 and 130 stations currently (Figure 3). There is a significant overlap between the stations used by each AC. Out of the 130 stations actively used in the IGS network, about 95 are used weekly by 3 or more ACs. Human and computer resource limitations are the main factors constraining the number of stations used by each AC. The ACs have continuously upgraded their software and approaches, which has resulted in gradual improvements of their solution results. Ideally, all the processed data should be done in a consistent manner. But, due to the large quantity of data and processing load involved, none of the ACs has yet to complete the reprocessing. On the hardware side, receiver/antenna, communication and computer technologies have also progressed, resulting in higher quality data, faster access and processing.



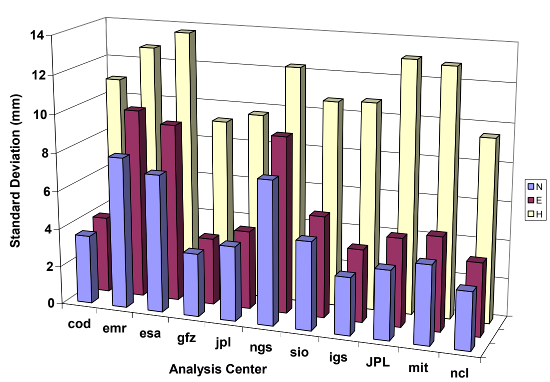
Number of AC/GNAAC/IGS stations in the weekly solutions
Figure 3

The standard deviations of residuals between the ITRF2000 and the IGS solution are summarized in Table 2. They show a horizontal position precision approaching the 1mm level and the vertical component approaching 3mm. The velocity precision is approaching 2mm/y horizontal while the vertical component is about 5mm/y. These are probably somewhat optimistic, since the GPS solutions in the ITRF2000 combination used, to a large extent a common set of IGS stations. As mentioned above, the common station coordinates are to a large extent derived from a common set of code and phase measurements.

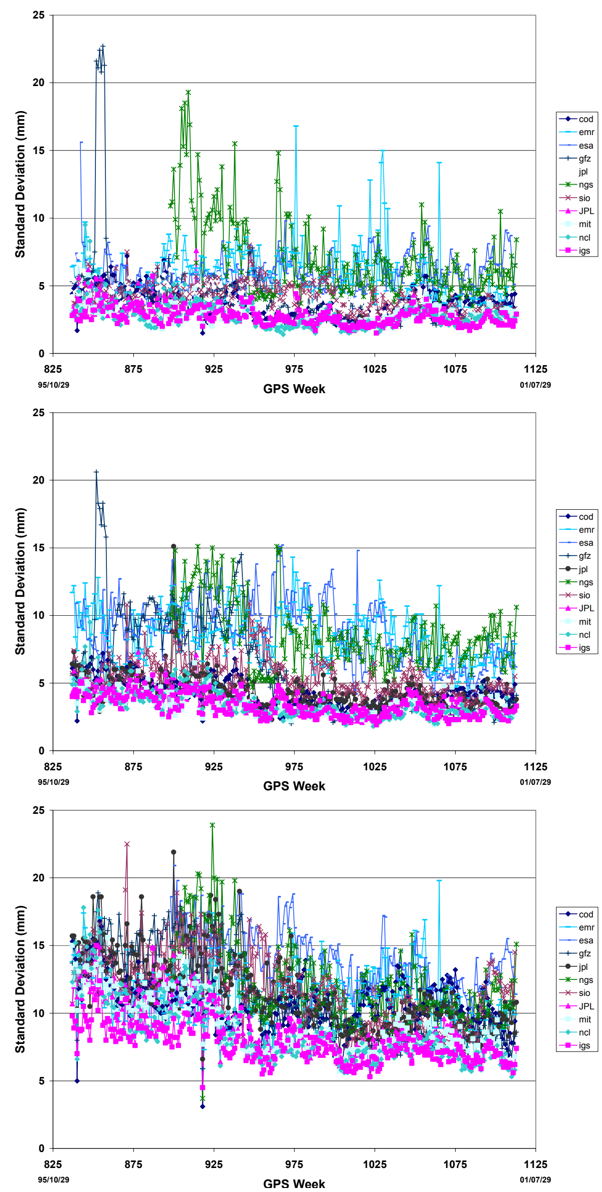
	Position (mm)	Velocity (mm/y)
Latitude	1.1	1.8
Longitude	0.9	2.3
Height	3.1	5.1

IGS standard deviations (STD) with respect to ITRF2000
Table 2

The standard deviations of the residuals between the weekly and the cumulative solutions for all stations have been estimated for each center (AC/GNAAC/IGS). Figure 4 a-b-c shows the time series of the standard deviations for the latitude, longitude and height components. The IGS and GNAAC standard deviations are 3-4mm horizontal and 7-10mm vertical (Figure 5). The ACs are also generally close to that level. Also noticeable is the gradual improvement of the statistics, especially in the height component (Figure 4c). The bandwidth of the standard deviations is also decreasing, indicating a better level of agreement between the various solutions. Similar improvements have been reported for the precise orbit/clock combinations also done weekly by the IGS AC Coordinator ([http://www.aiub.unibe.ch.acc.html)](http://www.aiub.unibe.ch.acc.html).



AC/GNAAC Station Coordinates Residuals STD with respect to. the Cumulative Solution
Figure 5

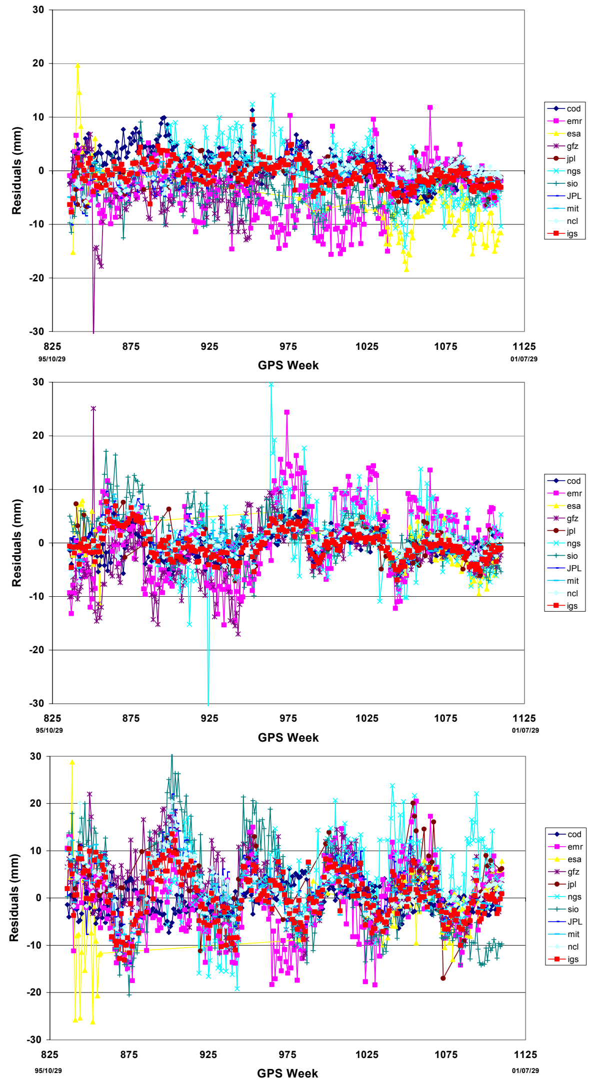


Latitude, Longitude and Height weekly STD with respect to Cumulative Combination
Figure 4 a-b-c

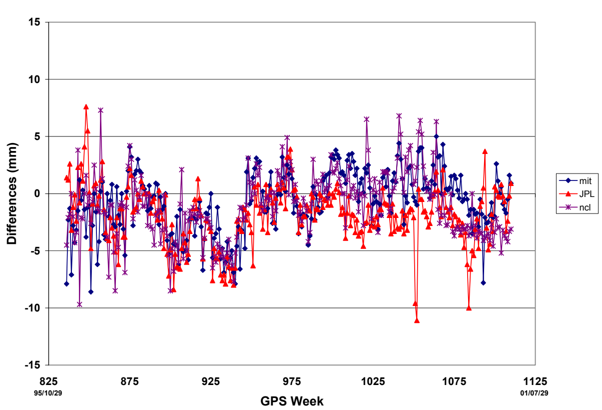
At the station level, a detailed look at the residual position time series shows the longer-term systematic effects present at some stations. For example, Figure 6 a-b-c shows residuals of the weekly AC/GNAAC/IGS solutions with respect to the cumulative solution for the latitude, longitude and height components at station Penticton

(DRAO). An annual period with amplitude of about 7mm is noticeable in the height component. Some periodic effects can also be seen in the longitude residuals. The level of agreement among the AC's also improves with time. The RMS of the residuals for the AC/GNAAC/IGS are respectively (Lat:5.4/2.4/2.4, Lon: 5.3/2.7/2.7, Hgt: 8.2/5.7/5.4). This station shows a rather large periodic signal (although not the largest). Most stations have little or no significant periodic signal. This periodic effect is possibly caused by variations in seasonal atmospheric pressure loading, which are not currently modeled in AC solutions. A detailed analysis of the periodic effects will be possible once the reprocessing is completed. Occasionally, biases do exist between the solutions, usually in the height component. Those biases are sometimes caused by incorrect antenna height used in the processing. The redundant time series are very useful to separate isolated outliers from ongoing biases. As part of the reprocessing of the AC solutions, a number of stations coordinate residuals time series discontinuities problems have been explained and corrected. Comparisons done in the past between the weekly and the cumulative solutions statistics have indicated that 60-70% of the noise is caused by short-term effects, while the rest has a longer-term signature. Those long-term signatures often take the form of discontinuities, which tend to affect mainly the height. They are generally caused by either blunders, equipment or processing changes.

Figure 7 shows height differences between the IGS and the GNAAC solutions at station Penticton. The standard deviation is 3 mm over a period of about 5 years. Differences of this magnitude are expected, due to differences in the processing strategies of the GNAACs. A small bias is apparent in the early weeks, a more refined analysis is expected to explain and potentially correct this artifact.



Latitude, Longitude and Height residuals between the weekly and cumulative solutions at station Penticton (DRAO)
Figures 6 a-b-c

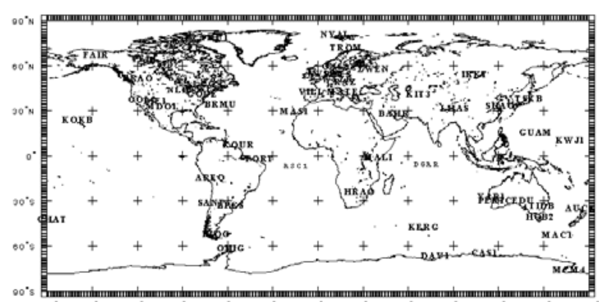


Penticton (DRAO) Height differences (IGS-GNAAC)
Figure 7

The reprocessing of the AC SINEX solutions between GPS weeks 0837 (96/01/21) and 0977 (98/10/03) is currently underway. Two iterations have at this time been completed. During the first iteration, the most obvious inconsistencies were removed. Nearly 9000 outliers were flagged. Explanations for many outliers could be found, thus allowing for corrective measures to be applied. A second iteration was run. This allowed to test the validity of the corrective measures applied to a number of weekly solutions, and to uncover new outliers. The exact number of iterations required is yet unknown. Once complete, the reprocessing will improve the quality of the weekly and cumulative solutions as well as its consistency and traceability by using a consistent strategy (Ferland et al. 2000). This reprocessing is using all the available information provided by the ACs and GNAACs. Each solution (AC/GNAAC) is unconstrained, its covariance information is rescaled with an estimated variance factor (chi squared per degree of freedom). AC/GNAAC station coordinates estimates are compared and rejected if they exceed the thresholds of 5 sigmas or 50mm (8 sigmas and 80mm for the first iteration). The residuals in the in the variance factor estimation are determined by taking the difference between each AC and the cumulative solution. The AC and GNAAC solutions are considered independent during the processing. In reality there is a significant level of correlation between the AC solutions mainly because they use the same code and phase observations for all the common stations. The differences between the AC solutions are mainly caused by variations in the processing strategies and the network distribution. A variance factor is also estimated and applied to the weekly IGS combination, again by using the cumulative solution as a reference. This should partially compensate for the neglected correlation between the AC solutions during the weekly solution combination. Similar correlations also exist between the IGS and the GNAAC weekly solutions. This is somewhat less of a concern, because the GNAAC are used mainly for quality control. The cumulative solution also needs to be rescaled, because the parameters covariance information gradually becomes unrealistically small as weekly solutions are added. More investigation is required to properly rescale the cumulative solution.

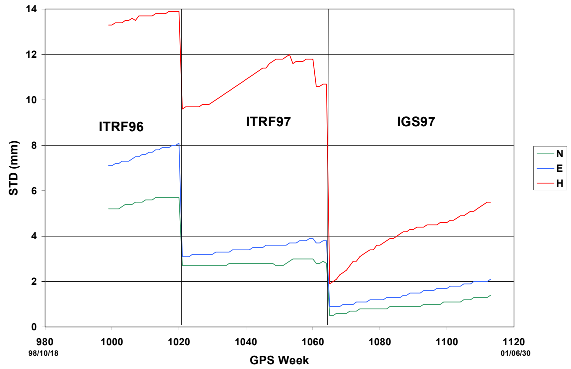
IGS REALIZATION AND DISSEMINATION OF ITRF2000

The current IGS realization of ITRF97 has been shown in Figure 2. It includes 51 globally distributed RF stations. The proposed set of stations to realize the ITRF2000 is shown in Figure 8. It currently includes 55 stations. All the proposed additions/changes are in the Southern Hemisphere with the objective to improve the station distribution. Two new stations are proposed in South America while one would be removed. Three other stations are proposed, one on Ascension Island in the Atlantic Ocean and one on Diego Garcia Island in the Indian Ocean as well as one in Australia.



Proposed IGS Stations for the Realization of ITRF2000
Figure 8

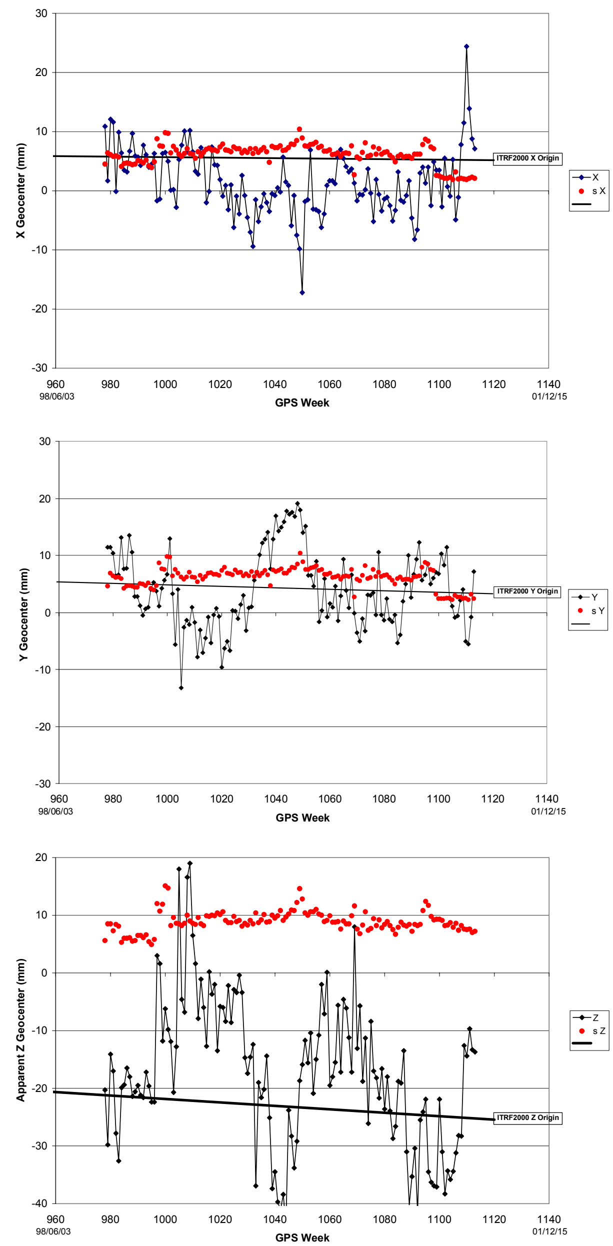
Figure 9, shows the quality of the fit between the successive IGS/ITRF realizations and the weekly updated cumulative solutions in ITRF96, starting with GPS week 0999 (99/02/28). There were already some improvements between the realization of ITRF96 and the original realization of ITRF97, and further improvements were made with the implementation of the IGS97. For ITRF96, ITRF97 and IGS97, the horizontal standard deviations went down from 5-8mm, to 3-4mm and to 1-2mm. In the vertical component they decreased from 13-14mm, to 10-12mm and to 2-6mm, respectively. The gradual degradation is caused mainly by propagated errors in the station coordinates and velocity of the reference frame realizations, as the extrapolation time increases. Preliminary tests done with the



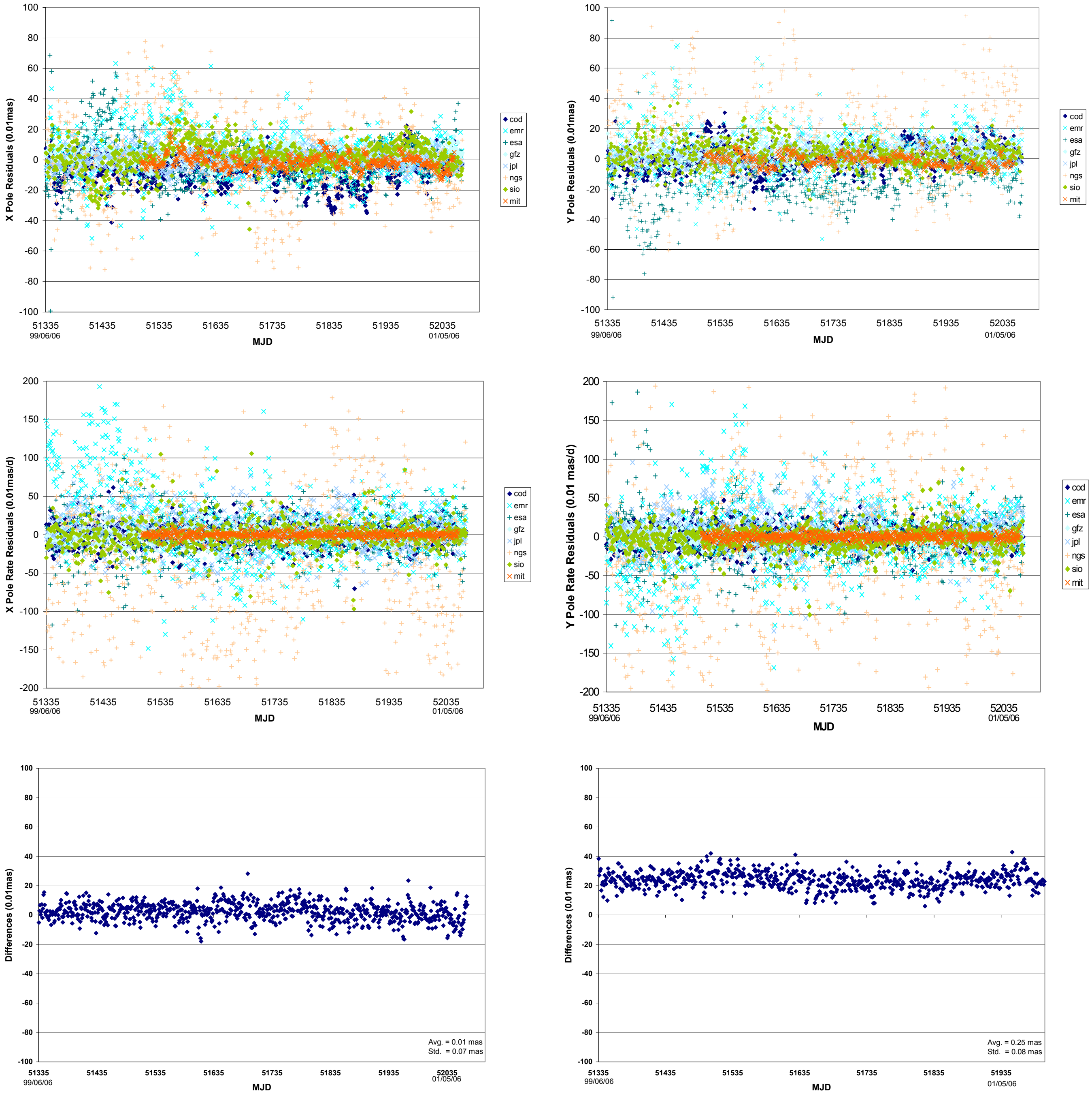
Weekly Reference Frame Station Coordinates Residuals STD between each Reference Frame Realization and the IGS Cumulative solutions
Figure 9

proposed IGS realization of ITRF2000 would result in sub-mm standard deviations for GPS week 1110-1114 (May 2001). The use of ITRF2000 directly would results in standard deviations of about 3mm horizontally and 6mm vertically for the same epoch.

The weekly estimated IGS geocenter is also affected by the proposed realization. Figure 10 a-b-c shows the X, Y and Z estimated geocenter with respect to the realization of ITRF97. The estimated weekly geocenter positions currently rely on COD, ESA and JPL SINEX solutions. The Figure 10 a-b-c also show the position of the origin of the proposed IGS realization of ITRF2000 with respect to ITRF97. The time series show an average offset 1.6mm, 4.0mm and –17.4mm for the X, Y, and Z components in ITRF97.



Apparent Geocenter Weekly estimates and formal sigmas as well as proposed IGS realization of ITRF2000 origin with respect to current IGS realization of ITRF97.
Figure 10 a-b-c



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.
Figure 11 a-b (top) c-d (middle) e-f (bottom)

The average offsets of the ITRF2000 geocenter for the same period are 5.5mm, 4.0mm and –22.7mm. This leaves a difference of 3.9mm, 0.0mm and 5.3mm for each component. This shows an improvement for each axis, specially the Z component.

The ERPs are combined in the weekly SINEX solution along with the station coordinates by making use of all covariance information. The best AC pole (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 11 show the daily time series residuals 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. 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 IGS combined values epochs. Small differences between the AC combined pole and pole rates are due to differences in processing strategy (e.g.: different weighting and rejection criterion). Similar daily ERPs 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 0.07mas which is similar to the differences with respect to Bulletin A (bias removed). The combined ERPs are consistent with those combinations at about 0.05mas (0.10-0.20mas/d).

SUMMARY

The IGS cumulative solution now contains about 270 stations among which 167 were submitted to ITRF for inclusion in ITRF2000. Analysis of the residuals of the ITRF2000 combination show horizontal/vertical position RMS of about 1mm / 3mm and horizontal/vertical velocity RMS of 2mm/y / 5mm/y. The IGS realizations of ITRF uses a subset of the IGS cumulative solution. This improves the internal stability and consistency of the weekly product alignment. The use of the 7 ACs and the 3 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 proposed 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/).

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