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ORIGINAL ARTICLE

The IGS-combined station coordinates, earth rotation parameters and apparent geocenter

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Abstract The International GNSS Service (IGS) routinely generates a number of weekly, daily and sub-daily products. Station coordinates and velocities, earth rotation parameters (ERPs) and apparent geocenter are among these products generated weekly by the IGS Reference Frame Coordinator. They have been determined since 1999 by combining independent estimates from at least seven IGS Analysis Centers (ACs). Two Global Network Associate Analysis Centers (GNAACs) also provide independent combinations using the same AC weekly solutions and they are currently used to quality control the IGS combination. The combined solutions are aligned to an IGS realization (IGS05) of the ITRF2005 using a carefully selected set of the IGS Reference Frame (RF) stations (nominally 132). During the combination process, the contributing solutions are compared and outliers are removed to ensure a high level of consistency of the estimated parameters. The ACs and the weekly combined solution are consistent at the 1–2 and 3–4 mm levels for the horizontal and vertical components. Similarly, the excess Length of Day (LOD), the pole positions and pole rates are consistent at the 10 µs, 0.03–0.05 mas and 0.10–0.20 mas/day levels, respectively. The consistency of the apparent geocenter estimate is about 5 mm in the X and Y components and 10 mm in the Z component. Comparison of the IGS-combined ERP estimates with the IERS Bulletin A suggests a small bias of the order of -0.04 mas and $+0.05$ mas (both ± 0.05 mas) in the x and y components.

Keywords IGS · Reference frame · Network · GPS

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1 Introduction

One important objective of the International GNSS Service (IGS) is to provide the highest quality products for the Global Navigation Satellite Systems (GNSS) in support of Earth science research, multidisciplinary applications and education.

These products are:

- precise GPS (GLONASS) satellite orbits,
- Earth rotation parameters (ERPs),
- coordinates and velocities of the IGS tracking stations,
- GPS satellite and tracking station clocks and timescale products,
- ionospheric and tropospheric delay parameters.

Since 1999, coordinates and velocities of IGS tracking stations, ERPs and coordinates of the apparent geocenter have been determined by combining independent estimates from at least seven Analysis Centers (ACs) (Table 1). Each AC contributes a weekly solution in the SINEX (Software INdependent EXchange) format. Since the beginning of 2008, a new AC (grg) has started to provide its SINEX contribution and is currently in the final stage of testing. The weekly AC SINEX products include weekly station coordinates estimates (up to about 250 stations), daily LOD and x/y pole positions and rates and weekly implicit apparent geocenter positions. All the IGS products should be unique, consistent and optimal. For the SINEX products, this is achieved by simultaneously combining in a standard least squares adjustment, the station coordinates, ERPs and the apparent geocenter from each AC using all its complete covariance information. To keep the combination parameters to a manageable size, other products such as satellite and station clocks, tropospheric delays, satellite orbits, etc. are combined independently within the IGS.

Table 1 Analysis centers (ACs) and Global Network Associate Analysis Centers (GNAACs)

AC	Description
cod	Center for Orbit Determination in Europe, AIUB, Switzerland
emr	Natural Resources Canada, Canada (Formerly Energy, Mines and Resources, Canada)
esa	European Space Operations Center, ESA, Germany
gfz	GeoForschungsZentrum, Germany
jpl	Jet Propulsion Laboratory, USA
MIT	Massachusetts Institute of Technology, USA
ngs	National Oceanic and Atmospheric Administration / NGS, USA
sio	Scripps Institution of Oceanography, USA
grg (new)	Groupe de Recherche en Géodésie Spatiale /CNES, France
GNAACs	
mit	Massachusetts Institute of Technology, USA
ncl	University of Newcastle-upon-Tyne, UK

2 Combination procedures

The main objective of the combination is to determine the best possible estimates for the parameters expressed in the current IGS realization (IGS05) of the ITRF. It is essential that the provided solutions follow the same agreed modeling convention, namely IERS 2003. The SINEX combination requirements were originally outlined in Blewitt et al. (1997) and in Kouba et al. (1998). Prior to the combination, the contributing solutions are pre-processed and checked for inconsistencies. The pre-processing ensures that the contributing solutions are:

(1) in the agreed SINEX format,
(2) unconstrained,
(3) corrected for local offsets and station name inconsistencies,
(4) augmented with explicit apparent geocenter,
(5) properly rescaled (covariance information),
(6) numerically conditioned (if needed).

After the inconsistencies are removed, the best estimates are determined during a standard least-squares adjustment. Potential coordinates inconsistencies are detected by comparing each contributing solution to:

(a) the Reference Frame realization,
(b) the other contributing solutions,
(c) the weekly combination of the previous week,
(d) the cumulative combination of the previous week.

The outlier detection threshold has two components: a statistical component currently set at 5 sigmas and an absolute component currently set at 5 cm. During the detection/rejection process, solutions (a), (c) and (d) are assumed to be correct since they have already been validated in the past. Any outlier is therefore expected to originate within the current contributing solution(s). The need to compare to the Reference Frame (a) is necessary to avoid biases when aligning the solutions. The comparisons to the previous week's weekly (c) and cumulative (d) solutions, although not strictly necessary, were found to be very useful to detect abnormal coordinate variations with respect to short and long term history. When outliers are found during the comparison between the contributing weekly AC solutions, both estimates are deleted.

The outcome of the statistical testing may be altered during the processing to either force the inclusion or deletion of specific stations. Occasionally, the assumption of correctness for solutions (a) and (d) may be incorrect. The two main causes are the non-linearity of the station coordinate model used in those solutions and/or a non-linear change in the current/recent estimation of the station coordinates. The first cause has been encountered most often with newly added stations (or station discontinuity) to the cumulative solution. Initial velocity estimates may be very poor, causing unreliable extrapolation and subsequently incorrect outlier detection. When allowed to be propagated for several weeks, those problems are characterized by a rapid increase of the outlier. In rare cases, poor velocity in the Reference Frame realization has caused outliers. They tend to show up after several years of extrapolation and are characterized by a very gradual outlier increase. This may happen when there is a small undetected discontinuity in the station coordinate time series.

Station coordinate time series discontinuities have been problematic in the proper interpretation of GPS results. Large discontinuities are easily detectable automatically. However, small discontinuities require a review of the coordinate positions and/or residual time series. Very small discontinuities may easily be interpreted as short term anomalies and vice-versa. In most cases, it is useful to have a few weeks of data to confirm the nature of the anomaly. All ACs estimating the same station coordinates are also expected to observe the same discontinuity. Auxiliary information such as station operator feedback and/or station logs and/or earthquakes reports that may explain an anomaly increases the confidence level of the decision made. Most of the discontinuities observed from the GPS station coordinate time series could be attributed to equipment changes but unfortunately some still remains unknown. The vast majority of the discontinuities found only affect the station coordinates although a few have been reported to affect the station velocities as well. Only a small number of discontinuities can be attributed to geophysical events such as earthquakes. Stations in the vicinity of large earthquakes may experience linear or non-linear velocity changes after the event.

The covariance information provided by the ACs and GNAACs need to be rescaled to be compared and combined in a meaningful way. The recent estimated scale factors, i.e. $\sqrt{Variance\ Factor\ or\ \sqrt{VF}}$, vary from approximately 1.5 to about 35. After rescaling the covariance information, the resulting formal sigmas between comparable AC parameters are generally within a factor 2. The scale factor used to rescale the solutions is determined by comparing the input solutions with the cumulative solution. It is then applied and iteratively refined until a convergence is attained (usually within two to three iterations). Scale factors from previous weeks are used as initial approximations for the current week. Week to week variations are generally within 10–15% with larger variations possibly indicating some AC processing changes. A scale factor is also estimated for the IGS-combined weekly solution. Its value is about 1.5 with variations in the order of 10%. This is needed to avoid unrealistically optimistic covariance information for the weekly combined solution. In the standard least-squares, the AC solutions are assumed to be independent but this is clearly not the case. The AC noise solutions can be divided into data and processing noise. Common stations found between ACs will most likely behave the same way and will show a highly correlated trend between ACs, thus limiting possible data noise reduction. However, as most AC use different software, their combined solutions will mainly reduce the processing noise.

3 IGS reference frame realization

The key objective of the IGS Reference Frame realization is to disseminate consistent, reliable and accurate products to improve the accessibility to the ITRF (Altamimi et al. 2007). The latest Reference Frame realization (IGS05) (Ferland 2006) has been used since 5 November 2006 (GPS week 1400). The most important reference frame station selection criterions are performance, monumentation, geometry and collocation. Only a few stations excel on all the above selection criterions. Although every effort is made to evaluate the stations objectively, there is some subjectivity in the final selection process. About 300 stations were originally considered for the latest Reference Frame realization out of which only 132 stations were retained.

The main changes with respect to the previous realization (IGb00) are an updated and augmented list of stations and a change from relative to absolute antenna phase center calibration. To account for the changes in phase center calibration, the ITRF2005 station coordinates were corrected for the effect of the differences between relative and absolute antenna phase center models on the station coordinates keeping the station velocities unchanged. Six ACs (cod, emr, gfz, mit, ngs, and sio) contributed solutions between GPS weeks 1325 and 1388 to estimate the effect on station coordinates due to the phase center model change. They provided solutions similar to their official IGS weekly contribution, except for the antenna phase center variation model. The solutions were compared and the effect on the coordinates was estimated for each station. The phase center change produced a scale offset of about 1.86 ppb which was removed by aligning IGS05 to ITRF2005 using a 7-parameters Helmert transformation (3 rotations, 3 translations and 1 scale). Note that antenna domes also affect the antenna phase centers but were originally ignored in the relative phase center models. Their effect is gradually being accounted for in the absolute calibration models. The number of Reference Frame stations usable for the alignment of the solutions generally decreases at a rate of about 10% a year. Currently, there are about 100 stations routinely used in the Reference Frame realization. The two main causes of this gradual reduction are station coordinate discontinuities and stations that are no longer used or simply “dormant”. The combined effect of the phase center model change and the change from the IGS00 to IGS05 realizations of ITRF2000 and ITRF2005, respectively, caused a reduction of the AC scale bias from over 3 ppb to less than 1 ppb as well as a reduction in the scale scatters between ACs.

4 Products of the IGS SINEX solutions

Station coordinates, ERPs and apparent geocenter are the three product components to the combined IGS SINEX solutions. As mentioned above, consistency is ensured by simultaneously and rigorously combining the product components in a least-squares adjustment. The GNAACs also provide independent solutions for the station coordinates and ERPs that allow to further assess the quality of the IGS weekly combined products.

4.1 Station coordinates

The ACs routinely include between 50 to close to 300 stations in their weekly contribution. Nowadays, the number of stations in the IGS weekly combined solution include close to 350 stations (Fig. 1). The evolution in the station usage by the ACs often changes in steps. Those steps often coincide with software upgrades. The geographical distribution of the processed/combined stations is shown in Fig. 2. The European and African regions are, respectively, over and under represented with respect to the overall distribution. The oceanic regions also tend to be under represented for obvious reasons.

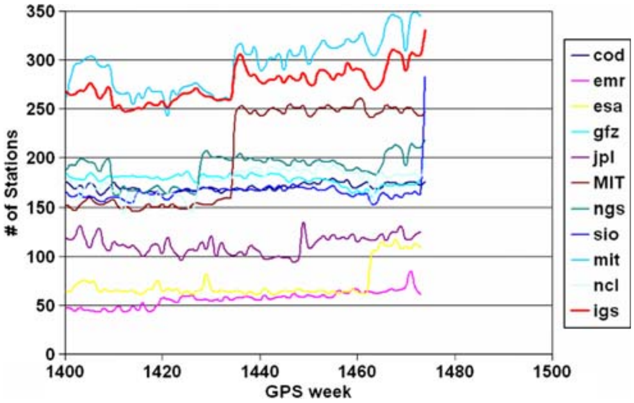

Fig. 1 Recent evolution of the number of IGS stations processed/combined by the ACs, GNAACs and IGS

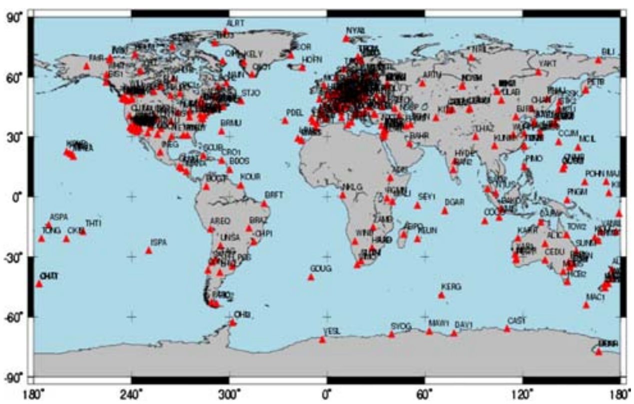

Fig. 2 Station geographical distribution in recent IGS weekly solutions

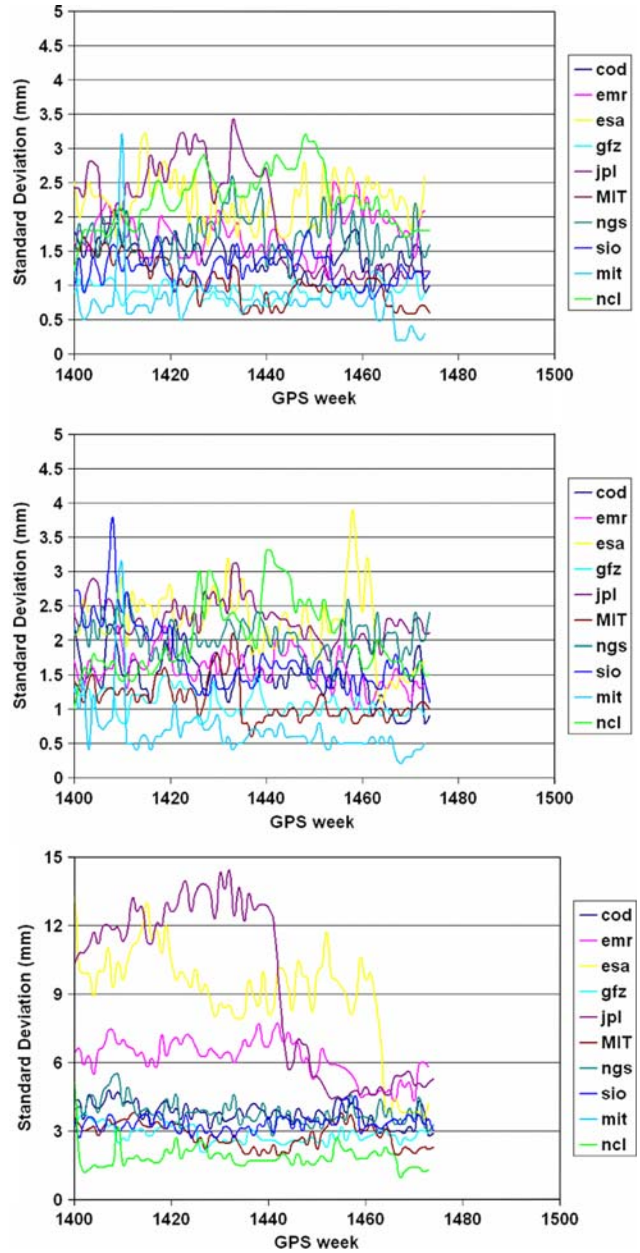

Fig. 3 Standard deviations of the station coordinate residuals between the weekly AC and GNAAC solutions and the IGS weekly combined solution (*Top* North, *middle* East, *Bottom* Height)

As part of the weekly combination, the quality of the input products as well as the Final combined products is estimated and reported to users via a publicly available summary file. The AC contributions, the Reference Frame realization, the IGS weekly and cumulative solution coordinates are compared and the average and standard deviations of the coordinate residuals in the north, east and up components are reported. The residual standard deviations between the ACs and the IGS weekly combination provide a measure of the internal coordinate consistency (Fig. 3). For recent weeks the consistency has been about 1–2 mm for the horizontal components and about 4 mm for the vertical component. When compared to the cumulative solution the standard deviations are, respectively, 2–3 and 7 mm for the same components. Those should be representative of the coordinate's accuracy (Fig. 4). In Figs. 3 and 4, esa and jpl show at weeks 1463 and 1445, respectively, a significant decrease in the standard deviation of their height components. For esa, the decrease coincides with the implementation of a new analysis software. For jpl the decrease coincides with the switch from a relative to an absolute antenna phase center model and the correction of a number of antenna offset inconsistencies. To avoid inconsistencies and biases in the combined weekly SINEX products, the jpl solution was not included in the combination between GPS week 1400 and 1445.

The GNAACs (mit and ncl) provide independent combination of the ACs weekly solutions. Figures 3 and 4 show as well the GNAACs level of consistency with respect to the IGS weekly and cumulative combinations. For recent weeks the

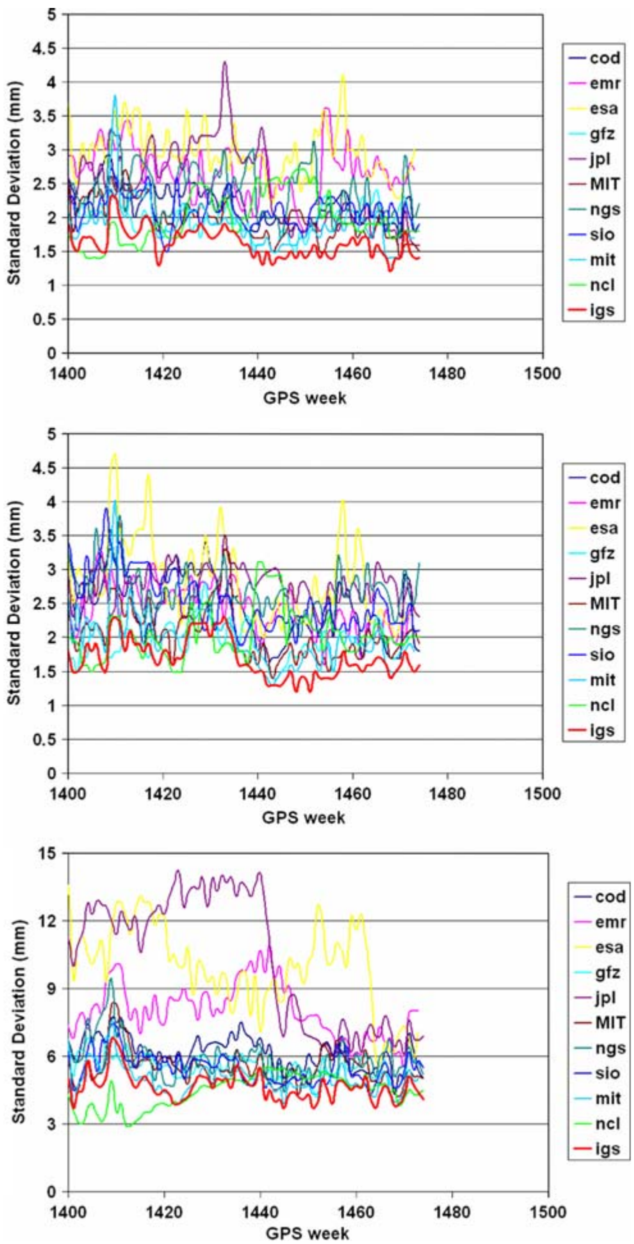

Fig. 4 Standard deviations of station coordinate residuals between the weekly AC and GNAAC solutions and the IGS cumulative combined solution (*Top* North, *middle* East, *Bottom* Height)

consistency of the weekly IGS combination with the mit combination in the horizontal and vertical components is about 0.5 and 1.5–2.0 mm, respectively. This is an indication of the level of processing noise between the IGS and mit combinations. The comparison is not as good with the ncl combination where possible unresolved constraints might be an issue. In Fig. 4, the statistics time series of the IGS weekly combination with respect to the cumulative combination solution are, as expected, generally the best.

4.2 Earth rotation parameters

Daily ERP estimates (LOD, pole positions and pole rates provided at noon of each day) are included in the weekly IGS SINEX combination. Only the ERPs for the week of interest are combined. Due to the linear dependency with the right ascension of the ascending node of the satellite orbits, the combination of the UT parameter requires some special attention and therefore is not currently considered in the IGS weekly combination.

The AC LOD estimates have some biases that are removed before the combination. The AC LOD biases are estimated from past LOD differences with respect to the IERS Bulletin A using a 21-day sliding window (Mireault et al. 1999). The average LOD difference with respect to the IERS Bulletin A is only $-1\,\mu s$ (Table 2) due to the bias corrections applied. ERP estimates with unremovable constraints are excluded from the combination. Figure 5 shows the residuals of the AC and GNAAC ERPs with respect to the IGS-combined solution. ERP comparison statistics of the IGS solution with respect to the GNNACs and IERS Bulletin A are shown in Table 2. The x and y pole position comparison with the IERS Bulletin A suggests that there is a small bias of, respectively, -0.04 mas and $+0.05$ mas (both at $\pm$ 0.05 mas). These biases are much smaller when comparing against the GNAACs, suggesting that these independent combinations are consistent at least at the 0.02 mas level. For weeks 1477–1506 the pole biases between IGS estimates and Bulletin A are below 0.01 mas. For recent weeks, the internal consistency of the AC LOD, pole positions and pole rates have been, respectively, at the $10\,\mu s$, 0.03–0.05 mas and 0.10–0.20 mas/day levels. The formal uncertainties from the adjustment are at the $5\,\mu s$, 0.02 mas and 10 mas/day levels. Comparison with the IERS Bulletin A suggests an accuracy of the order of $10\,\mu s$, 0.05 mas and 0.10 mas/day for LOD, the pole positions and pole rates, respectively.

4.3 Apparent geocenter

The main force acting on the satellites is the attraction from Earth's mass (solid, liquid and atmosphere). From the satellite orbits, it is possible to estimate the Earth's center of mass movement. This ability is mainly limited by the accuracy to model the other forces acting on the satellite (e.g. radiation pressure). The label "apparent geocenter" is used to reflect this limitation. By convention, the ACs apparent geocenter, as sensed by the satellite orbits is implicitly at the origin of the station coordinates provided in the SINEX products. Figure 6 shows the IGS-combined weekly apparent geocenter positions estimates and the formal uncertainty with respect to the IGS05. Indirectly, it also shows the level of consistency

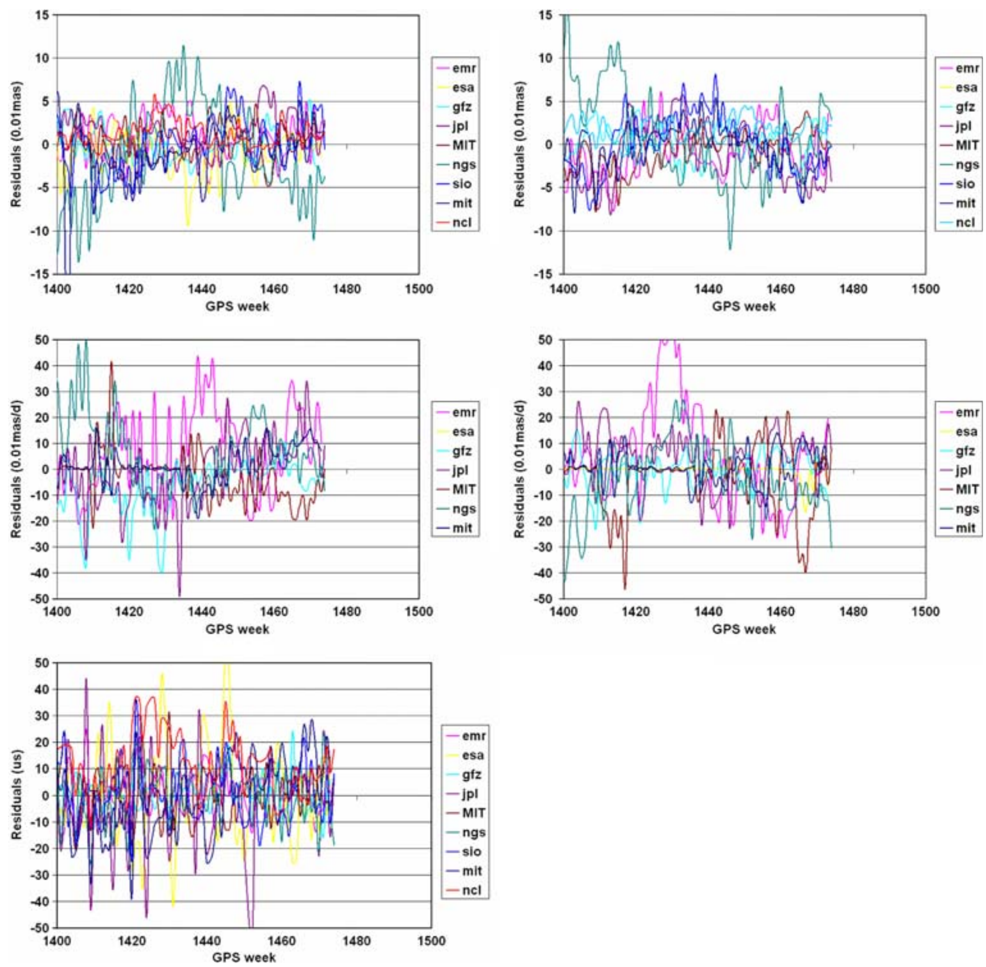

Fig. 5 AC and GNAAC *x* pole (*top left*) and *y* pole (*top right*) position residuals, *x* pole rate (*middle left*) and *y* pole rate (*middle right*) residuals and LOD (*bottom*) residuals with respect to the IGS weekly combined solution

Table 2 Comparisons (average and standard deviation) of the combined IGS daily ERPs with respect to the GNAACs (mit and ncl) and the IERS Bulletin A for GPS weeks 1400–1476

Solution	LOD μs	X pole 0.01 mas	Y pole 0.01 mas	X pole rate 0.01 mas/day	Y pole rate 0.01 mas/day
mit	3 ± 20	-2 ± 8	0 ± 4	3 ± 24	-1 ± 14
ncl	12 ± 12	1 ± 2	2 ± 2	N/A	N/A
IERS Bull.A	-1 ± 10	-4 ± 5	5 ± 5	-2 ± 12	0 ± 12

with the long term SLR time series used to determine ITRF05 origin.

The combined apparent geocenter time series show small bias of about 1.8, 2.2 and 2.5 mm in the X, Y and Z components, respectively. The formal weekly uncertainty estimates are at the 2.5 mm level in the X and Y components and the 4 mm level in the Z component with evidence of periodicities. Figure 7 shows the residuals of the contributing ACs apparent geocenter. NGS (not shown in Fig. 7) was recently added to the estimation of the apparent geocenter. The residuals are generally at or better than 5, 5 and 10 mm in the X, Y and Z components, respectively. The residuals between the ACs show repeating weekly bias.

5 Summary

The combination and comparison procedures provide the necessary information to assess the overall quality of the input AC product components and the output IGS products.

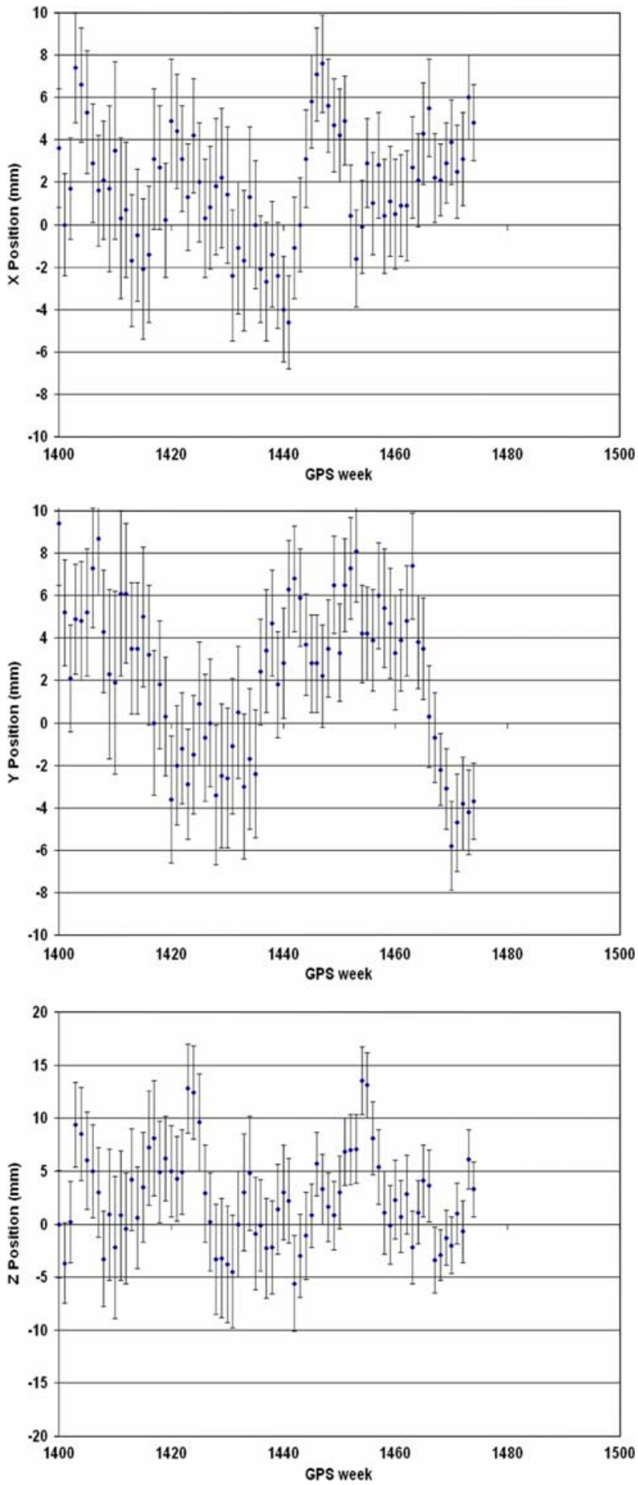

Fig. 6 IGS-combined weekly apparent geocenter with respect to IGS05 (X, Top; Y, Middle; Z, Bottom)

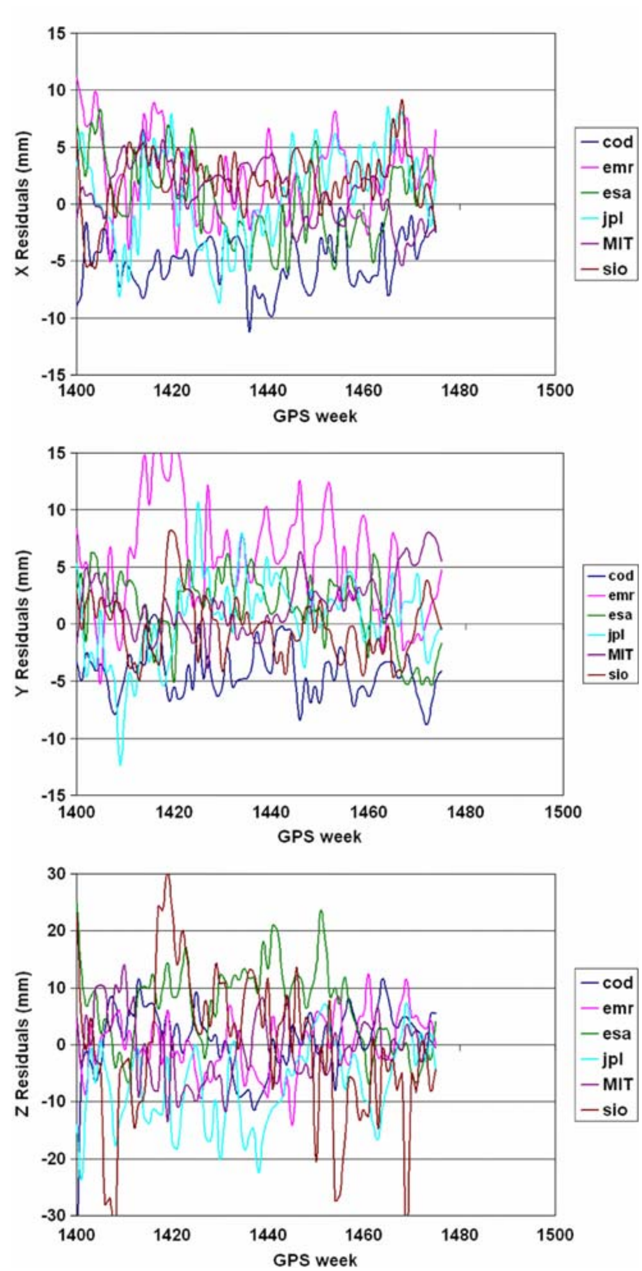

Fig. 7 AC apparent geocenter residuals with respect to the IGS weekly solution (X, Top; Y, Middle; Z, Bottom)

The overall quality of the SINEX IGS products has been assessed in three different ways: internal consistency, formal uncertainty and external comparisons. The first two ways generally provides very similar estimations and are more

Table 3 SINEX product accuracy of recent IGS weekly SINEX solutions

Parameter type	Component	Accuracy
Coordinates (weekly)	Horizontal	2–3 mm
	Vertical	7 mm
Apparent geocenter (weekly)	X and Y	5 mm
	Z	10 mm
ERPs (daily)	Pole positions	0.05 mas
	Pole rates	0.10 mas/day
	LOD	10 μs

optimistic than the external comparison. The formal uncertainty is more an indication of the internal IGS SINEX products consistency than a real accuracy. Comparison between the AC coordinates residuals statistics with respect to the reference frame and with respect to the weekly combination suggest that the internal consistency and accuracy may in some cases reach a factor 2. A summary of the external comparison is given in Table 3.

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