Quality and consistency of the IGS combined products

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Abstract

The quality and consistency of the IGS Analysis Centers' (ACs) contributions to the IGS combined products have steadily improved over the last years. The agreement among the Final/Rapid orbits is now at or below the 2 to 3 cm level for most of the ACs. The weekly network solutions have consistencies (standard deviations) of 1 to 2 mm and 5 to 6 mm for the horizontal and height components, respectively. With this high level of precision, smaller unmodeled or incorrectly modeled effects and various AC model inconsistencies are starting to be visible. All these inconsistencies will have a measurable effect on the combined products. Therefore, it is very important to reach the highest level of consistency of the AC solutions. In this paper the basic IGS Products are investigated for existing inconsistencies, in particular the possible inconsistencies between the orbit and the SINEX products are examined.

Station positions obtained by Precise Point Positioning (PPP), using IGS combined orbits and clocks as well as those from individual ACs, are inspected for biases with respect to the IGS realization of the ITRF (IGb00). Furthermore, the effects of using various ocean tide loading models on daily mean stations position and geocenter solutions are computed and compared.

1 Introduction

The level of consistency between various IGS products is correlated with their overall precision and accuracy. Therefore, the precision of the core products, measured by the differences of individual Analysis Center products with respect the combined ones, shall be inspected first. With steadily increasing solution precision and quality, even smaller inconsistencies are starting to be visible. All the AC solution inconsistencies may also have a measurable effect on the combined products.

Existing biases could have various reasons and not all of them are understood yet. They may originate from unmodeled or incorrectly modeled effects, or simply from using different models (e.g. ocean tide loading) or different parameters (e.g. elevation cut-off angles) as well as from various methodological approaches. In order to give an idea of possible sources, below are listed some inconsistencies among the ACs:

- ocean tide loading models: GOT00.2, FES95.2, Schwiderski
- orbital arc lengths: 24 to 72 hours
- elevation cut-off angles: 3^o, 7^o, 10^o or 15^o, some with elevation dependent weighting
- clock alignment, either to the ITRF origin, or to the solved Earth's center of mass
- initializations and mapping functions of the troposphere delay model

The IGS products can benefit from new model development, like 2nd order ionospheric corrections, atmospheric tidal loading, both of which are often at the mm-level only. However, only when the inconsistencies/biases amongst the AC solutions of the same as well as different types (e.g., Final and

Rapid) are mitigated and the remaining biases become negligible, the IGS combined products can fully benefit from such new developments.

2 Quality of IGS products

The IGS products, i.e. the individual AC's and the combined ones, have been continuously improving thanks to the joint effort of all the contributing ACs as well as the whole geodetic community, that has been improving models for various components.

The majority of the AC Final orbit solutions now agree with the IGS combined orbits at or below the 2-cm level (Figure 1). The AC Rapid orbit solution agreements are also approaching the 2-cm level. The IGS Rapid and the IGS Final combined orbits agree even better, at about 1 cm. At this point, it should be mentioned that the submissions by ESA and NGS have significantly improved in the last two years. Therefore, to represent the current situation, the most of the statistics presented here will start on the GPS week 1321 only.

The AC SINEX network solutions (Figure 2) show very small biases for the mean of all stations, namely at the level of ±2 mm, ±1 mm and ±2 mm for the north, east and height component, respectively. The standard deviations for the horizontal components are approaching ±1 mm and for the height ±4 mm.

IGS generates two Final series of the Earth Rotation Parameters (ERP). Namely, one from the SINEX combination (igs00p02), which is the official IGS ERP series, as well as an independently combined one (igs95p02), which is using the same weights as in the orbit combination and is still generated for continuity and consistency reasons. In Figure 3 the Final and Rapid ERPs from all ACs as well as the combined Rapid and the official SINEX ERP are compared to the historical igs95p02 series. The standard deviations of the best ACs are ±30 µas, ±35 µas and ±20 µs for the Final x_P, y_P and LOD, respectively. The corresponding differences for the combined Rapid ERPs are -5±30 µas, -33±30 µas and -1±10 µs, which are of the same level seen for the AC's comparisons, but the bias of the Rapid y_P should be of some concern and should be monitored carefully. The agreement of the official SINEX ERP with the historical igs95p02 series is very good, with 3±14 µas, -4±16 µas and -3±10 µs for the x_P, y_P and LOD, respectively. (Note that on the Earth surface 10 µas ≅ 0.3mm and 10 µs ≅ 4.5 mm.)

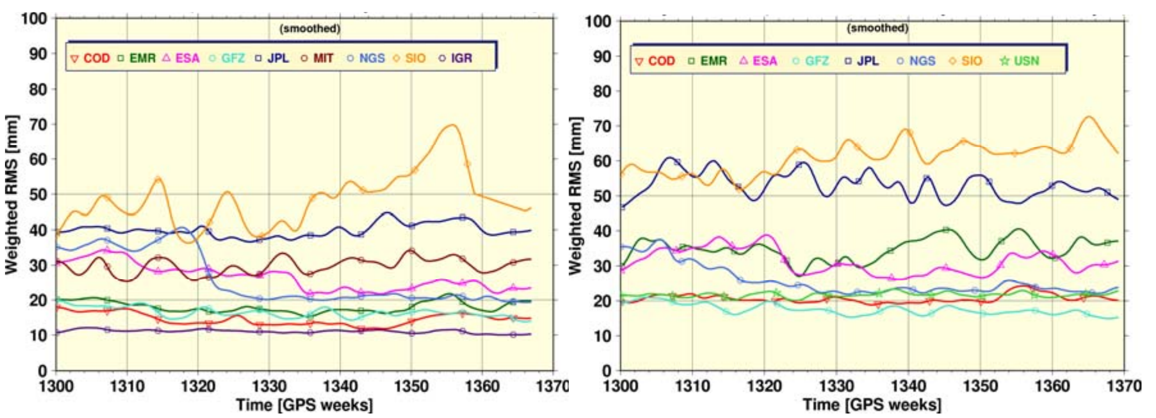

Figure 1. Quality of AC Final (left) and Rapid (right) orbits compared to the corresponding combined IGS orbits. The combined IGS Rapid orbits (IGR) are also compared to the IGS Final (left).

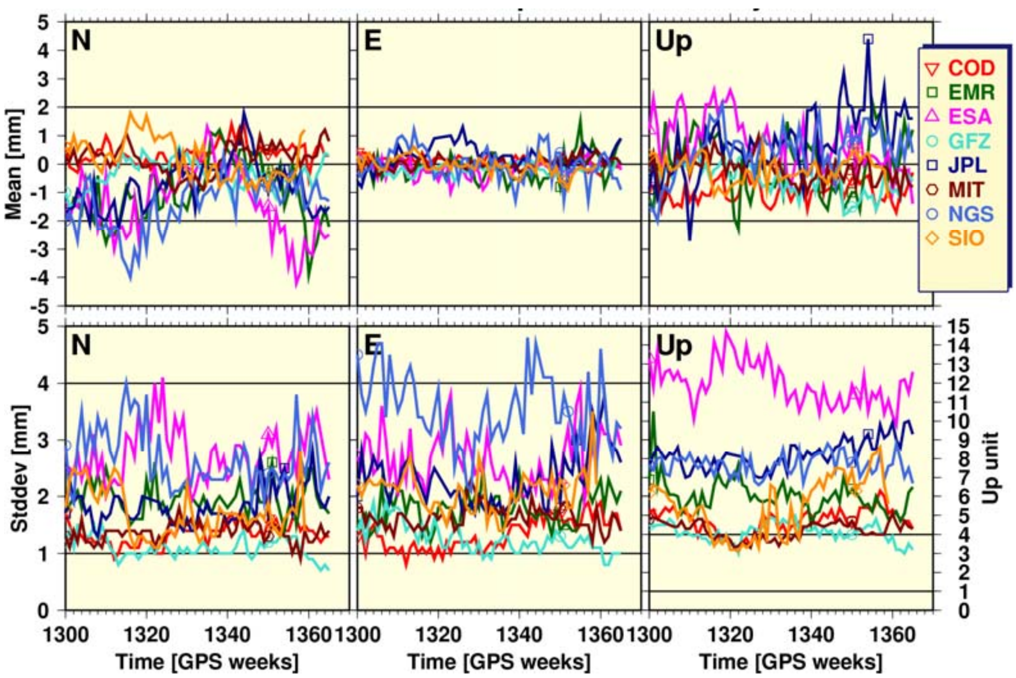

Figure 2. Comparison of the network solutions of the AC SINEX submissions with respect to the weekly combined IGS SINEX.

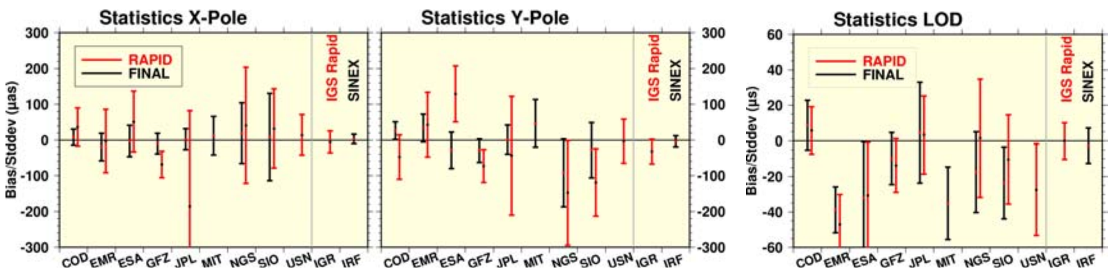

Figure 3. Statistics of the differences between the AC Final & Rapid ERP solutions and the combined IGS Final ERPs (igs95p02) during GPS weeks 1321 to 1362. The differences of the combined IGS Rapid and the official IGS SINEX ERPs (igs00p02) are also shown.

3 Spectral analysis for Earth Rotation Parameters

For each of the AC Final ERP solutions a spectral analysis was performed in order to check the consistency and possibly also to detect some problems. As inputs to the analysis the residual series from the IGS SINEX ERP combination (igs00p02) were used during the interval of July 2004 to December 2005.

Polar motion *(*Figure 4, *top and middle)*

As can be seen here, NGS has a stability problem in particular for longer periods (at and above 100 days). ESA has a seasonal and/or longer period problem (x_p amplitude > 0.04 mas) and a semi-annual peak in y_p (amplitude ~ 0.03mas). However, it should be mentioned that NGS and ESA results have improved significantly during this time interval and their newer results may not have the problems any more.

SIO has a semi-annual peak of almost 0.04 mas in x_p. EMR's x_p spectra show a rather strange effect with peaks of about .02 mas at 10-11 (~10.7) days. Currently, there is no explanation for this strange behavior.

Only small peaks can be seen at the fortnight band (14.2 days for x_p). Here all ACs except MIT have a small, though hardly significant, peak at about 0.01 mas. No such peaks can be seen for y_p. It should be noted that the 14.2-day period is likely the beat period against 24 hours of the 25.8-hour period of the O1 sub-daily ERP term.

LOD (Figure 4, *bottom)*

All the AC LODs had a good long-term stability during this period, since all ACs had only small or no peaks at seasonal and longer periods.

Since ESA has many significant peaks, they are not interpreted here.

MIT and JPL have semi-annual peaks of about 0.01 ms.

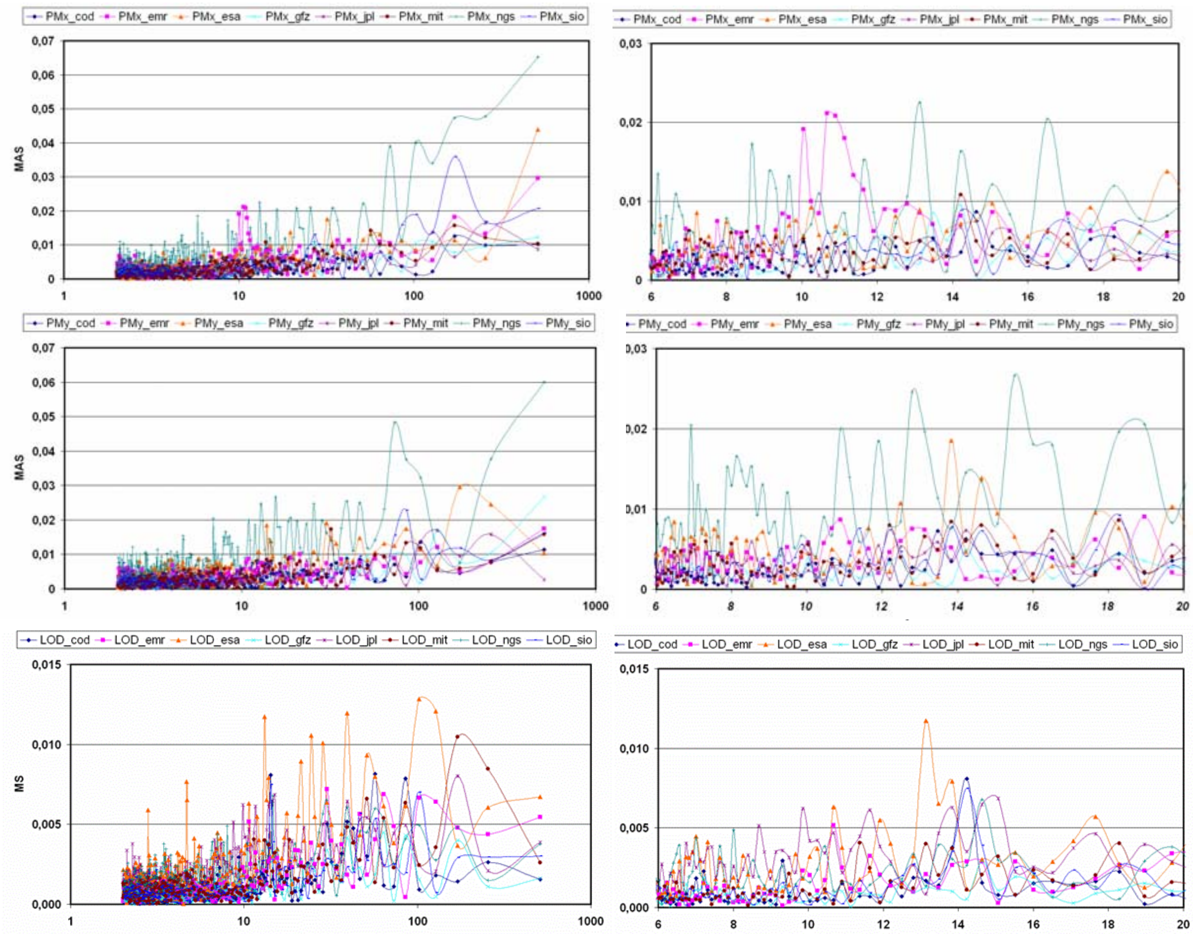

Figure 4. Amplitudes for polar motion in x (top, left and right), polar motion in y (middle, left and right) and LOD (bottom, left and right) during July 2004 to December 2005. The frequency is given in days. The 99% significance level is 0.01 mas (for NGS 2-3 times larger) and 0.003 ms.

COD and SIO have significant peaks at 14.2 days, which are likely due to the O1 term of the sub-daily ERP model. Because the other ACs have no such peaks, this likely means that the sub-daily ERP model (the O1 term) used by COD and SIO ACs are inconsistent with the model used by the rest of ACs during this period. Consequently, it is recommended that all ACs check if they are using the latest IERS sub-daily polar motion model. For more details about the sub-daily ERP effects on daily ERP solutions, see e.g., Brzezinski et al., 2004, Kouba, 2003.

4 Consistency of AC orbit and SINEX products

In Figure 5 the scale of the SINEX network solutions for each AC is given during the last two years. Except for some jumps, mostly connected with major software and approach changes of the ACs (see e.g., ESA), the SINEX scale for each AC is rather stable. The AC dependent scale values may be caused by differences in chosen models and parameters, like elevation cut-off angles and troposphere mapping functions. The orbit scales are also AC dependent. For each AC the difference between the SINEX and the orbit scales is quite stable in time, but varies from AC to AC (Figure 6, left). There is still no satisfactory explanation for these scale differences and their behavior.

The orbits and the network solutions should be given in the same reference frame by all ACs. This consistency can be tested by comparing the Helmert transformation (with respect to IGb00) of the AC SINEX network solutions and the transformation of the AC Final orbits with respect to IGS Final combined orbits. However, the SINEX translation parameters are first corrected for the IGS geocenter solutions to make them compatible with the IGS Final orbits. The agreement in the translation parameters (geocenter) is, in nearly all cases (Figure 6, middle), at the level of ± 5 mm (bias), with standard deviations of ±4 mm in x, y and ±8 mm in z. For most ACs, the rotation parameters (Figure 6, right) also have a fairly high consistency of ±0.1 mas, with even smaller standard deviations (±0.05 mas). Only JPL, with especially large discrepancies in x-rotations, is a notable exception. When inspecting the time series of the rotations (Figure 7) one can easily see the larger inconsistency between the orbits and SINEX solutions for JPL solutions, which needs to be checked and improved in the near future.

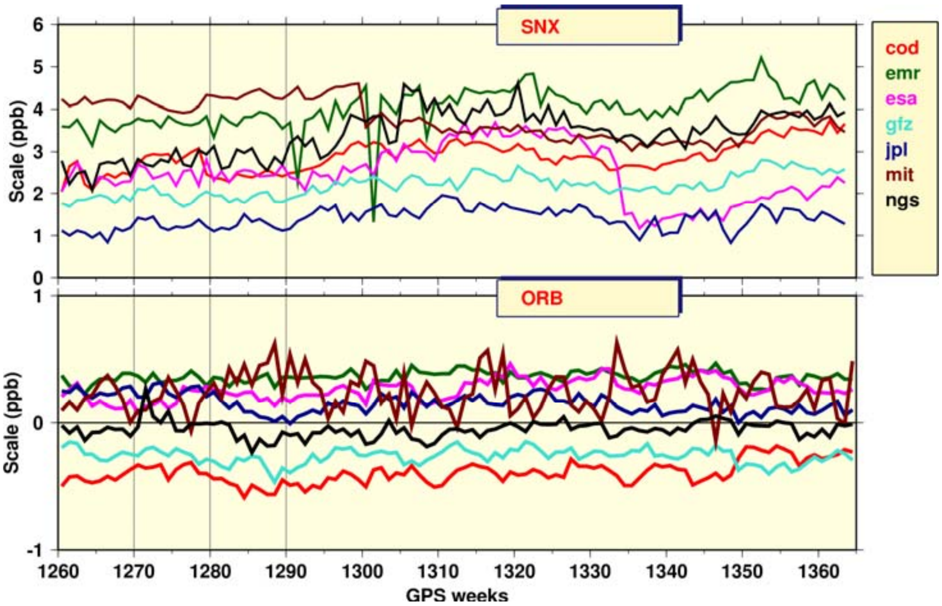

Figure 5. Scale differences of the AC SINEX solutions with respect to the IGb00 (top) and scale differences of the AC orbits compared with respect to the combined orbits (ORB).

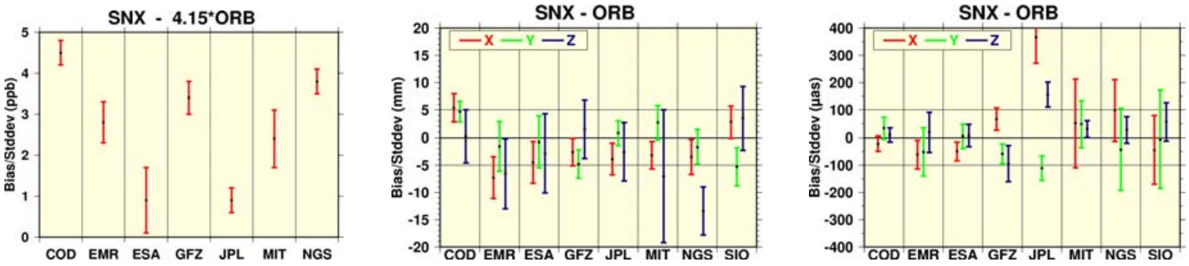

Figure 6. Statistics of differences between the AC SINEX solutions and AC Final orbits for scale (left), geocenter (middle) and rotations (right) during GPS weeks 1321 to 1362.

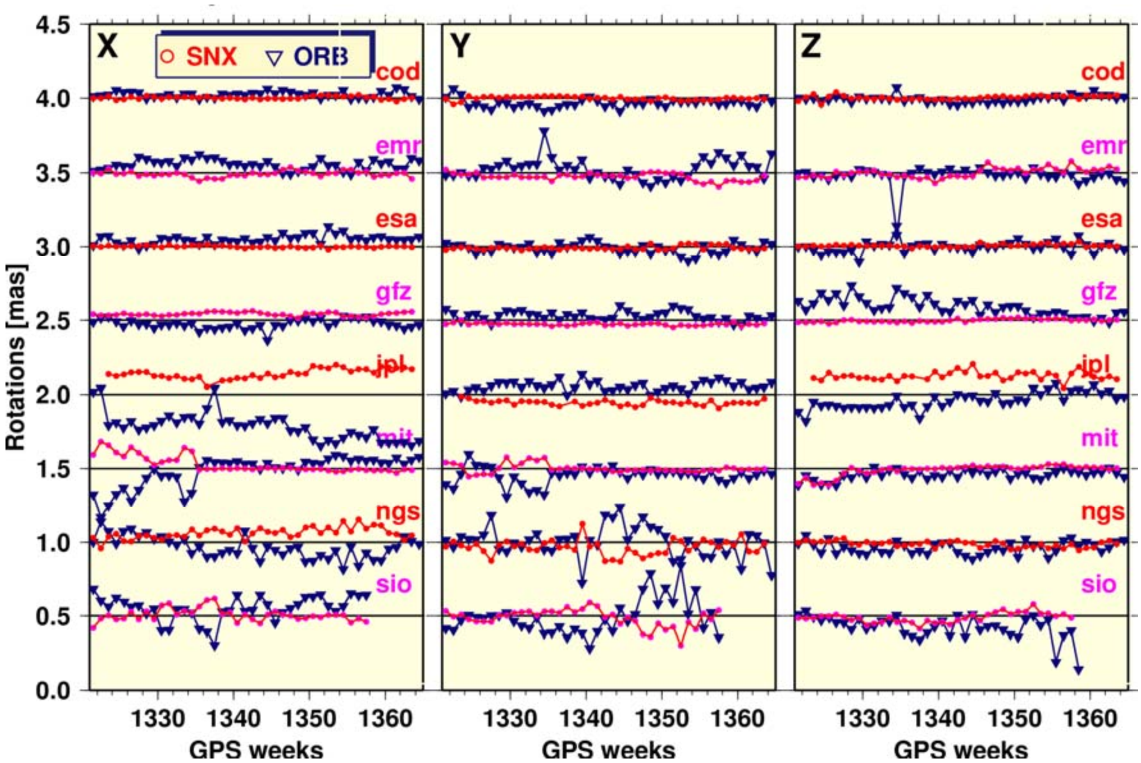

Figure 7. Consistency between rotation parameters of AC SINEX station coordinates with respect to IGb00 (SNX) and the rotations of the AC orbits with respect to the combined IGS Final orbits.

5 Consistency of PPP products

On a weekly cycle, all the Final and Rapid orbit/clock solution products are being used in a daily Precise Point Positioning (PPP) to validate the quality and consistency of the used products (http://www.gfz-potsdam.de/igsacc). In the examples below, all the ACs, which contribute to the Final combination, were chosen. Here, the PPPs are using the 5-min-clocks from the clock RINEX files and are performed for all the stations defining the IGS reference frame IGb00, about 90 each week. A Helmert transformation to the IGb00 then gives a measure on the consistency of the realization of IGS reference frame and the quality of the obtained station position solutions.

Figure 8 shows the Helmert (x, y, z) translation parameters (geocenter) of PPP solutions, using all the AC Final and Rapid products with respect to IGb00 during an interval of two years. Here, the translation parameters of the weekly AC SINEX solutions (SNX) are also shown. In most cases, the consistency of the Final and Rapid PPP solutions is fairly high, at a few mm and the station coordinates are referenced to the center of IGb00 (ITRF – the center of the network (CoN)). The only exceptions are EMR and JPL, their Final clock solutions are consistent with their SINEX solutions, which are referenced to the solved centre of mass (CoM). The IGS Final clock combination will be affected by this inconsistent clock origin handling among the ACs and the corresponding PPP solutions will then be referenced to a mixture of the CoN and CoM. The ACs should be reminded to adopt the recommendation RFM11 of the IGS Workshop 2004 held in Bern (Meindl, 2004): *"All IGS satellite clocks should be in ITRF CoN. ... ACs should fix their shifted station coordinates while back substituting for final clocks."*

The consistency between the Final and Rapid PPP rotations (Figure 9) is about 0.1 mas, or even smaller, i.e., all PPP solutions are in the IGb00; also the SINEX products are consistent at the same level for the latest time interval. The only exception is JPL, while the Final and Rapid PPP rotations are consistent, they both experience an offset with respect to IGb00 and the JPL SINEX solutions. This is caused by the rotational problems, which were already seen for the JPL orbits (Figure 7). This means that the submitted JPL orbit and SINEX solutions are not consistent as required for IGS orbit combinations and thus mandated by IGS.

Similarly, the PPP scales (Figure 10) show a good agreement between the Rapid and Final PPP solutions. However, the PPP scale offset of ~1 ppb with respect to the corresponding SINEX scale, seen for most of the ACs, is not yet understood.

Figure 11 summarizes the PPP results for the combined IGS Rapid and IGS Final products. As expected from the inconsistencies of CoN realization for some Final clock products seen earlier for some ACs, the combined Rapid translation parameters are smoother than those for the Finals. For the other parameters (rotation, scale), the agreement is equally good and neither IGS combined product performs better.

For the time series of PPP station coordinate solutions a frequency analysis was also performed during July 2004 to December 2005. Only five stations were selected: Algonquin Park (alg – Canada), McMurdo (mcm – Antarctica), NyAlesund (nya – Norway), Wettzell (wtz – Germany), Kourou (kou – French Guyana). Seasonal periods are seen in most of the IGS PPP results. The largest seasonal peak is seen for the mcm height and is likely not real (Figure 12, top), it is mainly due to the Niell Mapping function deficiency in the Antarctica region, which is causing seasonal errors at the 10-mm level (Boehm et al. 2006). Furthermore, there are site specific problems (Ray, 2006). PPP results using the products of the other ACs (COD, GFZ - Figure 12, bottom) show no agreement in seasonal and longer (semi-annual) periods, which also underlines the dominance of modeling problems for those frequencies.

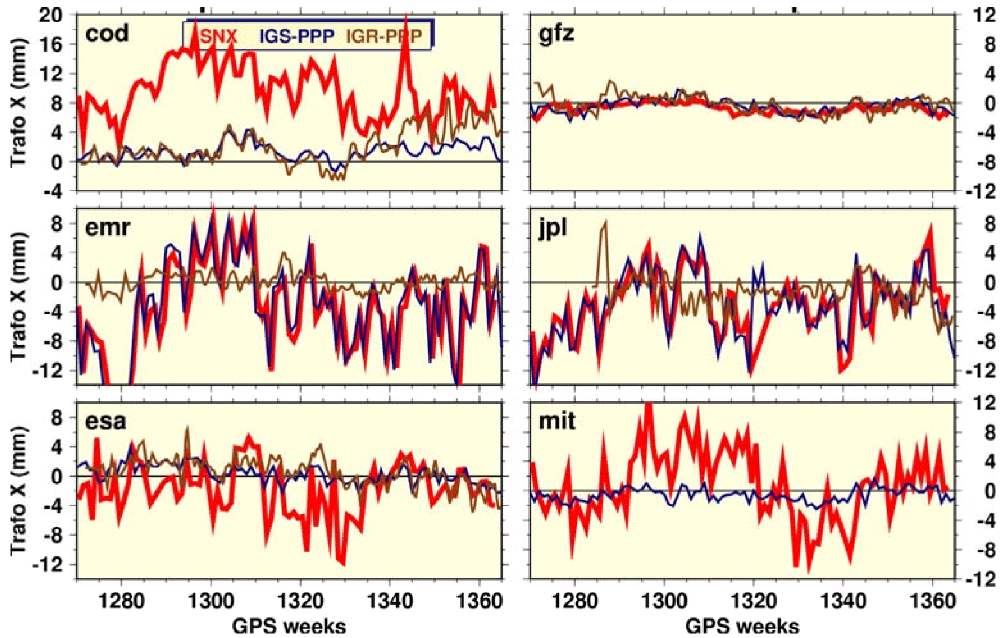

Figure 8. Daily Helmert translation parameters (x, y, z geocenter) of PPP solutions, using Final and Rapid AC products (Final – IGS; Rapid – IGR), with respect to IGb00. The translation parameters of the weekly AC SINEX solutions (SNX) are also shown. (Note that GFZ is constraining their weekly SINEX origin.)

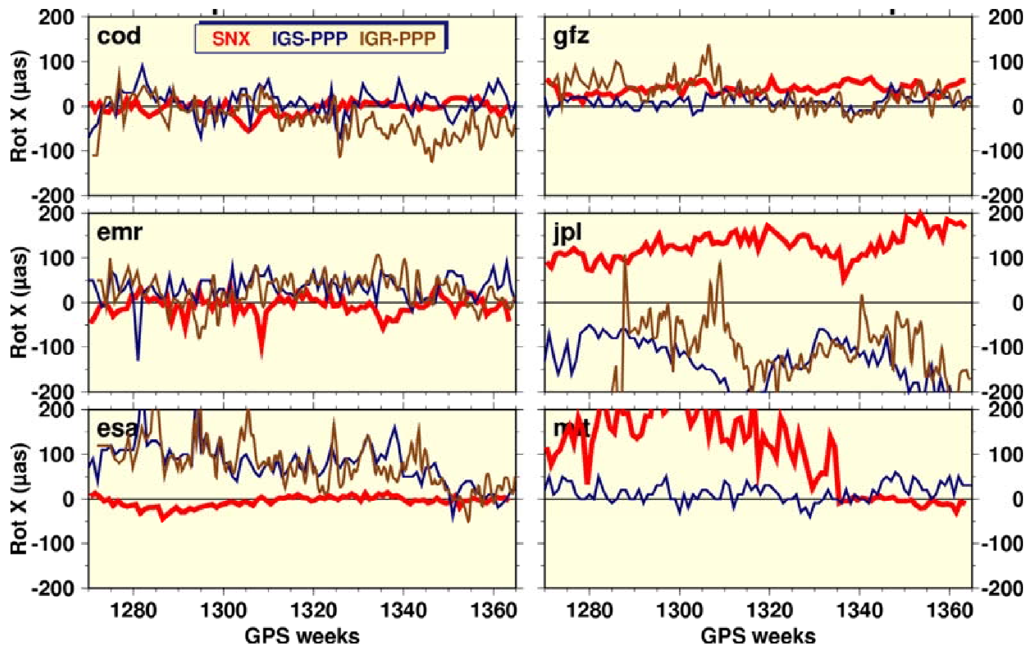

Figure 9. Daily Helmert x rotation parameters of PPP solutions, using Final and Rapid AC products (Final – IGS; Rapid – IGR), with respect to IGb00. The rotation parameters of the weekly AC SINEX solutions (SNX) are also shown.

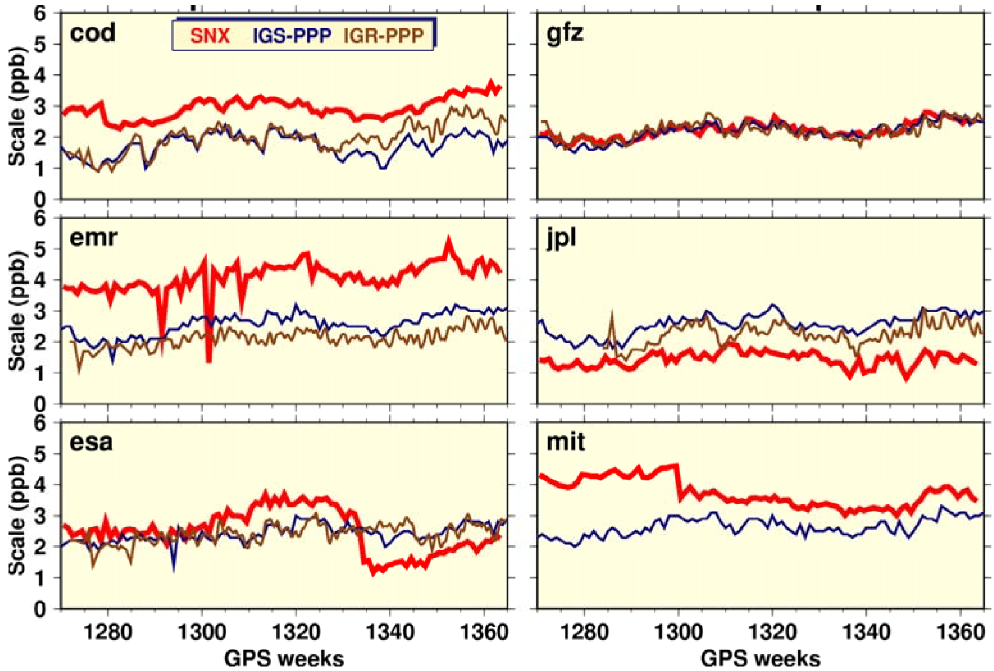

Figure 10. Daily scale of PPP solutions, using Final and Rapid AC products (Final – IGS; Rapid – IGR), with respect to IGb00. The scales of the weekly AC SINEX solutions (SNX) are also shown.

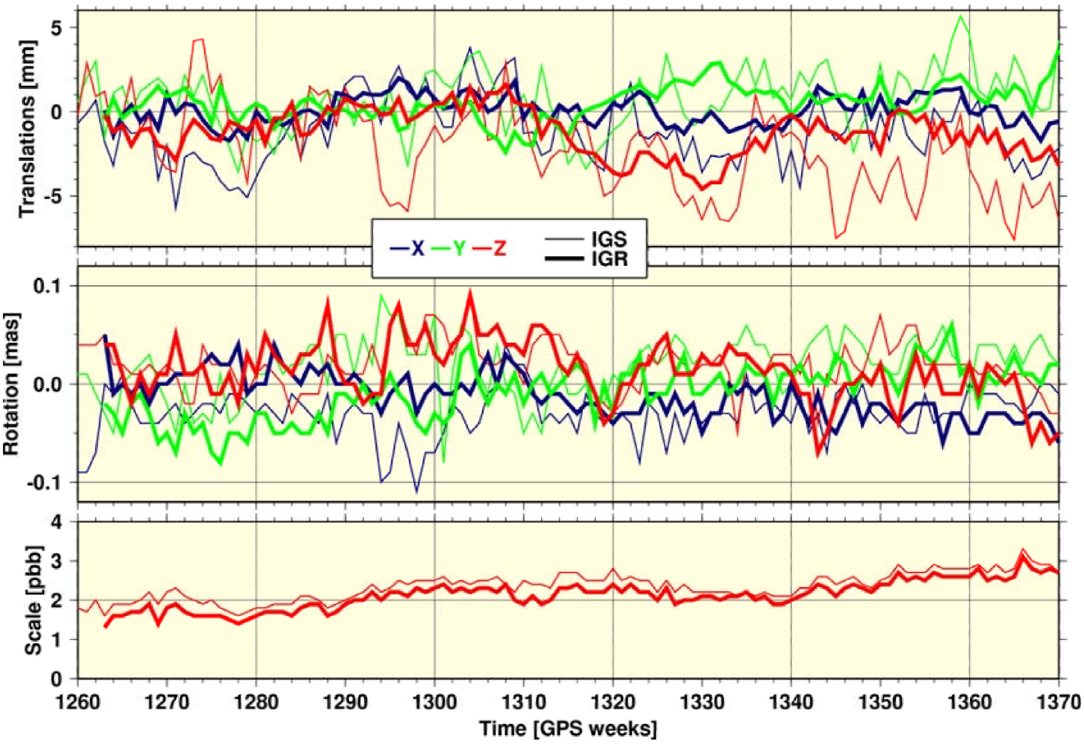

Figure 11. Daily Helmert transformation parameters of PPP solutions, using combined IGS Final and IGS Rapid products, with respect to the reference frame IGb00.

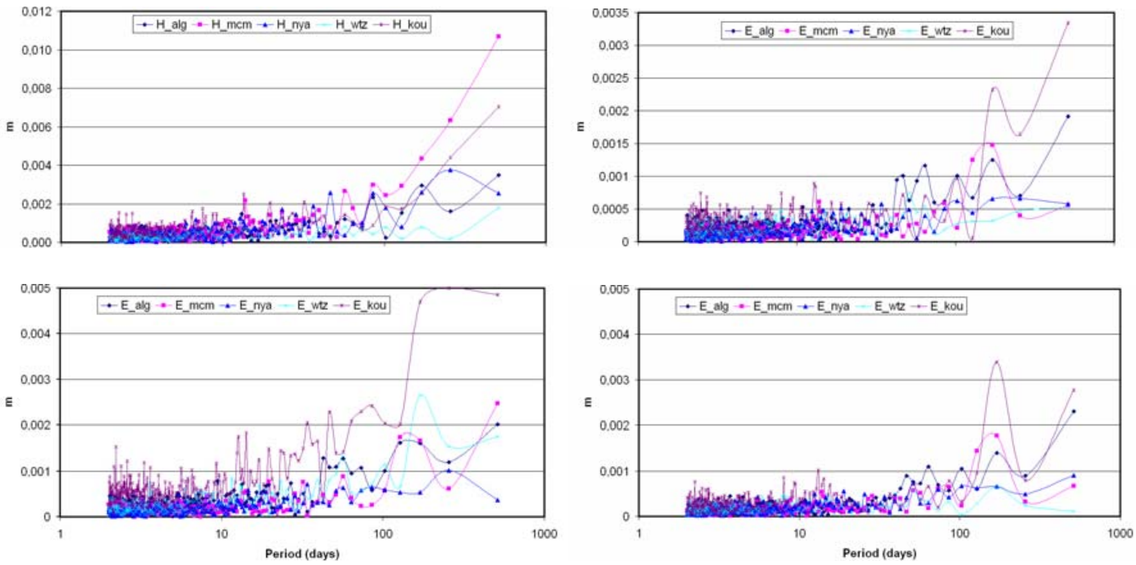

Figure 12. Amplitudes for position of selected stations (see text) of the height and east coordinate solutions from PPP with combined IGS product (top, left and right). Also shown are the east coordinate solutions of PPP with COD (bottom, left) and GFZ (bottom, right) products, during July 2004 to December 2005. The frequency periods are given in days. The 99% significance level is about 3-5 mm for the east and 5-10 mm for the height coordinates.

6 Aspects of ocean tidal loading

Currently, different ocean tidal loading models are used by the IGS ACs, although ACs are switching to the recent model GOT00.2, which is used here as a reference in all the subsequent comparisons. However, older models are still used by ESA, GFZ, MIT and SIO. If one compares the daily means of ocean loading displacements (Figure 13), which will be, more or less, mapped directly into the corresponding 24-hour station coordinate estimates, one can see mean loading differences (with respect to GOT00.2) of up to 3 mm. Such inconsistencies will then also enter into all the IGS combined products. Inspecting more modern models, such as FES2004, the differences are much smaller and amount to a few tenths of a millimeter only.

Similar inconsistencies can be seen for geocenter motions, induced by the ocean tidal loading. The daily mean geocenter differences among the ocean tide models can reach up to 2 mm, mainly with a yearly period (see the mean geocenter difference between GOT00.2 and Schwiderski models in Figure 14). Again, the differences among the newer models, such as GOT00.2, FES2004 and TPX.7.0 are much smaller and are below 0.15 mm only.

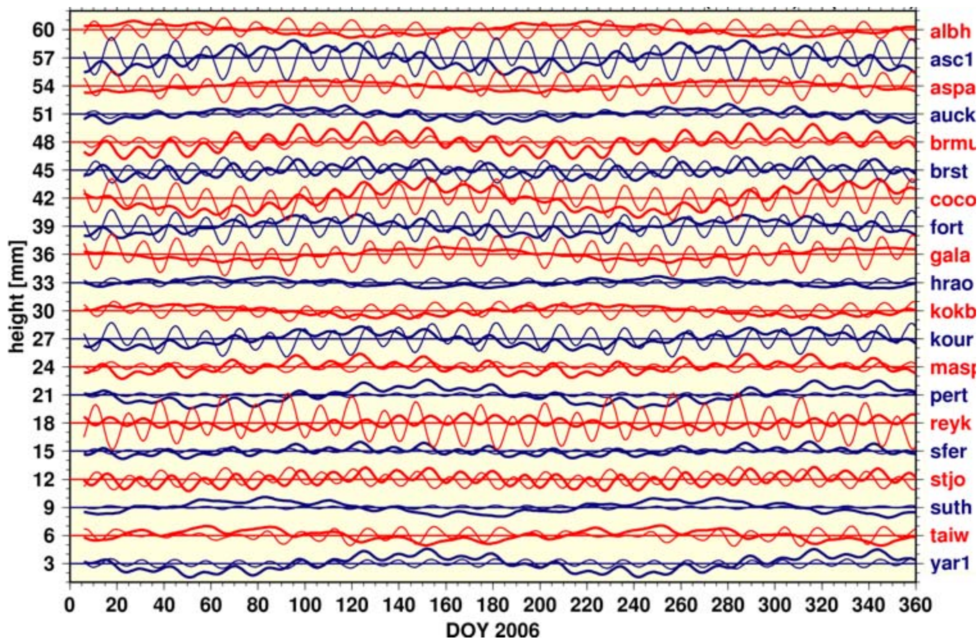

Figure 13. Comparisons of daily mean loading displacements in the height component for selected sites. Differences of Schwiderski model (thick lines) and FES95.2 (thin lines) with respect to the GOT00.2 model are plotted.

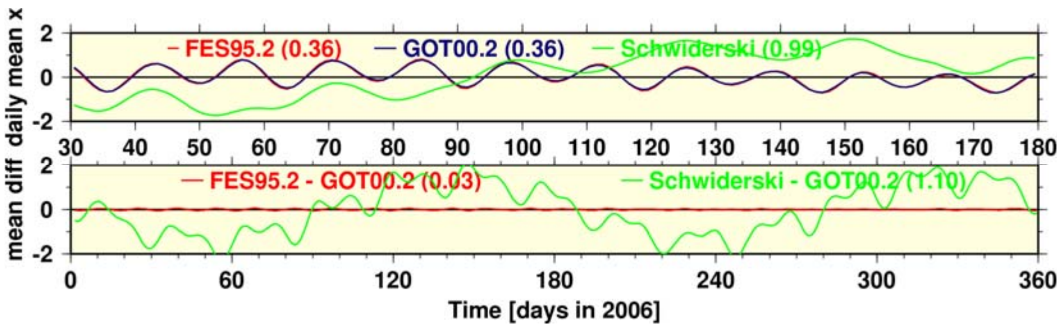

Figure 14. Daily means of ocean tidal geocenter motion for selected ocean tidal loading models (top) and differences between them (bootom). Unit: mm.

7 Summary

The quality (precision) of the IGS AC products has steadily improved during the last years. The IGS combined products can fully benefit from these ongoing improvements only if the consistency among the AC's products and even among the various product lines (Final, Rapid and Ultra Rapid) is kept up commensurately with AC product improvements. There are some obvious problems, which have to be solved first, like the rotational biases for JPL and the ITRF transformations of EMR and JPL Final clock solutions. More detailed studies are necessary to identify the reasons for the AC dependent scale offsets.

All ACs have agreed to use the ocean loading model FES2004 with center of mass corrections (the HARDISP routine shall be used here), which will help to reduce the inconsistency in the network solutions.

Because of visible amplitudes at the 14.2-day period in the ERP spectral analysis, all ACs should verify if they are using the sub-daily model of the IERS Conventions 2003.

No new special recommendations will be listed here. However, all ACs should carefully check if they are following the recommendations of the last IGS Workshop 2004, held in Bern (Meindl, 2004). Furthermore, it is essential that all ACs, for their routine IGS processing, start to follow all the recommendations given for the IGS reprocessing activity (Steigenberger, et al., 2006).

8 References

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