Products produced under the direction of the AC Coordinator: Processes, accuracies and quality control

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Abstract

Over the 10-year history of the IGS the accuracy and consistency of the IGS products have been improved dramatically. Being now at a level of centimeters for the orbits/clocks (0.1ns) and millimeters for station coordinates/Earth rotation parameters (ERP), for many customers the reliability and integrity of the products become as much important as a further improvement of the accuracy.
To get a better insight into the strengths and weaknesses of the combined products for orbits, clocks and ERPs a short description of the combination procedures is given, with special attention to quality checks and consistency.

1 Combination processes and product quality – An overview

The combined orbit, clock and ERP products are generated under the directions of the Analysis Coordinator and will be considered in this paper only. The inputs for the combinations are the submissions from the Analysis Centers (AC), which comprise:

- Orbits with 15-min satellite clocks (files: *.SP3, clocks optional)
- Earth rotation parameters (files: *.ERP)
- Clocks (5-min satellite & station clocks) (files: *.CLK; optional) (not for Ultra Rapid)

The clock products are optional, but in case of existing 5-min clocks the 15-min SP3 clocks are sampled from the CLK-file. The Final products are submitted 10 days after the end of the GPS week, the Rapid products each day after 17 hours, and the Ultra Rapid products twice a day (00 and 12 UT) after 3 hours.

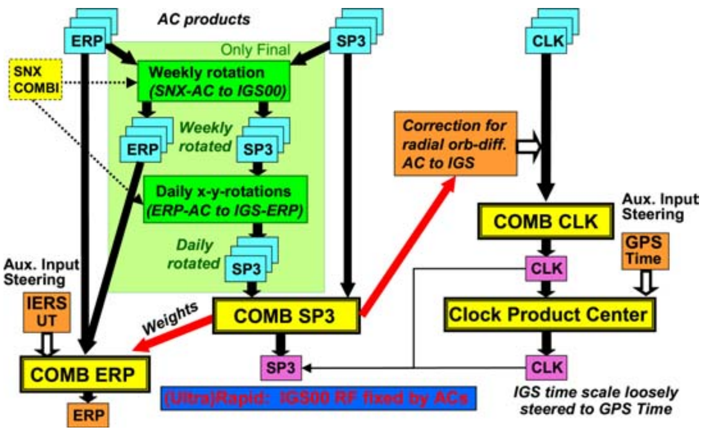

Fig. 1. Overview for the combination of orbits, clocks and ERPs

The Ultra Rapid products contain in addition to the solution for the last 24-hour data interval also orbit and clock predictions for the next 24 hours. During the generation of the Final products the ACs are performing a free network adjustment, whereas for the other products the station coordinates are fixed to the given IGS realization of the International Terrestrial Reference Frame (ITRF) (since 2004 the IGb00 realization with 99 stations).

An overview of the procedures is given in Figure 1. The starting point of all the product generation is the SP3 combination. For compatibility, the weights from the SP3-step are then used for the ERP combination. Satellite techniques are not able to derive UT and have also biases in the estimated length of the day (LOD). Therefore, the UT values are aligned to the IERS Bulletin A by integrating the (before calibrated) GPS LOD values starting at a given Bulletin A value for UT. It has to be mentioned that the official ERP product for the Finals comes since 2000 (GPS week 1051) from the SINEX combination, but a combined ERP product is still generated here for consistency check purposes (the difference to the SINEX solutions is only 0.05 mas with even smaller bias). The combined orbit is also used to perform clock corrections. The radial orbit differences of the individual AC orbits are accounted by

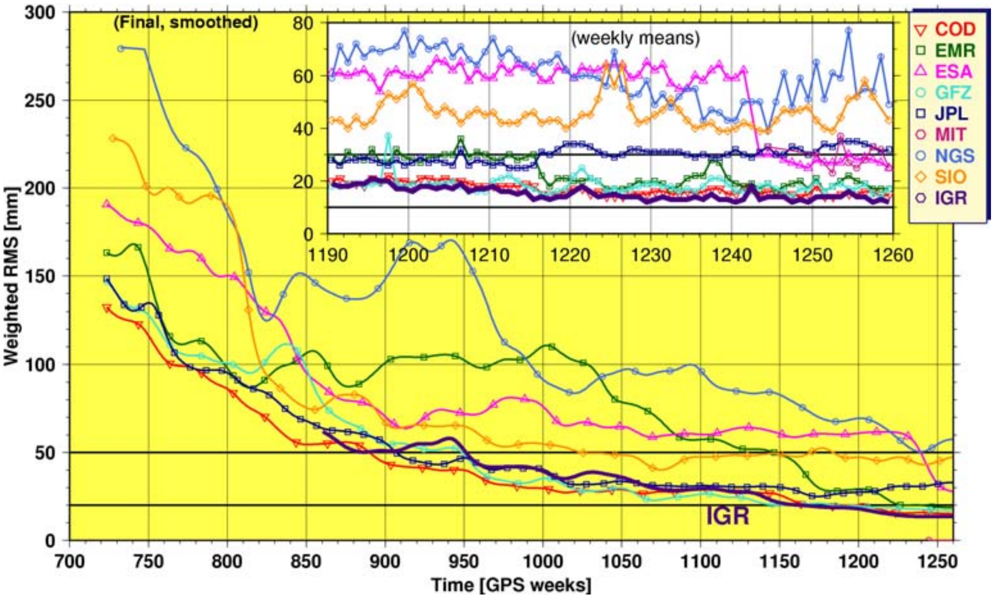

Fig. 2. Differences of Final AC and Combined IGS Rapid (IGR) orbits to combined IGS Final orbits from October 1993 (GPS week 720) to February 2004 (1260). A zoom for the last 60 weeks is given.

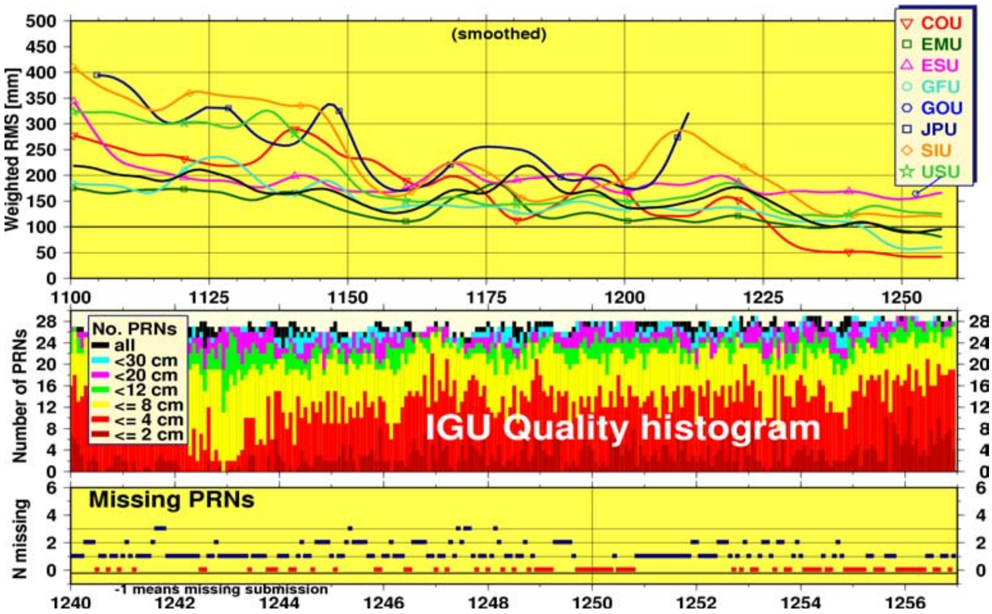

Fig. 3. Differences of IGS Ultra Rapid predicted orbits (first 12 h) to combined IGS Rapid orbits

$$dCLK_{AC} = ((SP3_{AC} - SP3_{IGS}) * SP3_{AC}) / R_{sat} / c, \quad (1)$$

with R_{sat} - radius to satellite, c- speed of light,

which at the same time also correct for geocenter differences in the AC orbit realizations. The "raw" combined clocks show jumps at day boundaries and also occasionally during the day by AC clock biases at phase offsets related to the larger P-code noise. In the Clock Product Center a much more stable clock product (Senior, 2001) is generated by loosely steering the 'raw' clocks at each epoch to GPS Time. The applied clock changes do not affect the clock differences within one epoch and therefore also not the precise point positioning (PPP) results. Starting in March 2004 the improved clock products are now the only official IGS clock products and are distributed with the combined orbits and clocks.

A special attention is given to the Final ERP and SP3 combination to ensure the consistency with the IGS reference frame (RF) realization. From the weekly SINEX combination, which is based on loosely constrained AC solutions, the AC rotation parameters are taken to align the ERP and SP3 products to the IGb00 (the latest RF realization since January 2004) before the combination. The SP3 products are in addition corrected for the daily scatter in the RF realization.

The consistency of the products has dramatically improved over the history of the IGS for mainly two reasons: (1) the quality of data (receiver upgrades) and their global coverage his improved by the common effort of the whole IGS community, (2) the software and models for analyzing the data has significantly improved by the friendly competition among the various involved ACs. From Figure 2 the development in the consistency and quality of the Final orbits can be seen. Starting at a level of about 15 to 20 cm, today a level of 2 cm between the best ACs is reached. Looking into the zoom for the last year one can recognize that the consistency to the Rapid orbit (IGR) is even approaching the 1 cm level. A similar improvement was gained for the clocks, where the internal consistency (subtracting a bias and a trend for each satellite and station) is now at the 0.05 ns level, enabling a cm-accuracy for the PPP.

The Ultra Rapid orbit predictions are of special importance for many applications. For them the quality was also steadily improved and went even below the 10 cm level since about GPS week 1230 (Fig.3, top). Looking into the history of the prediction quality for all single satellites it can be seen that

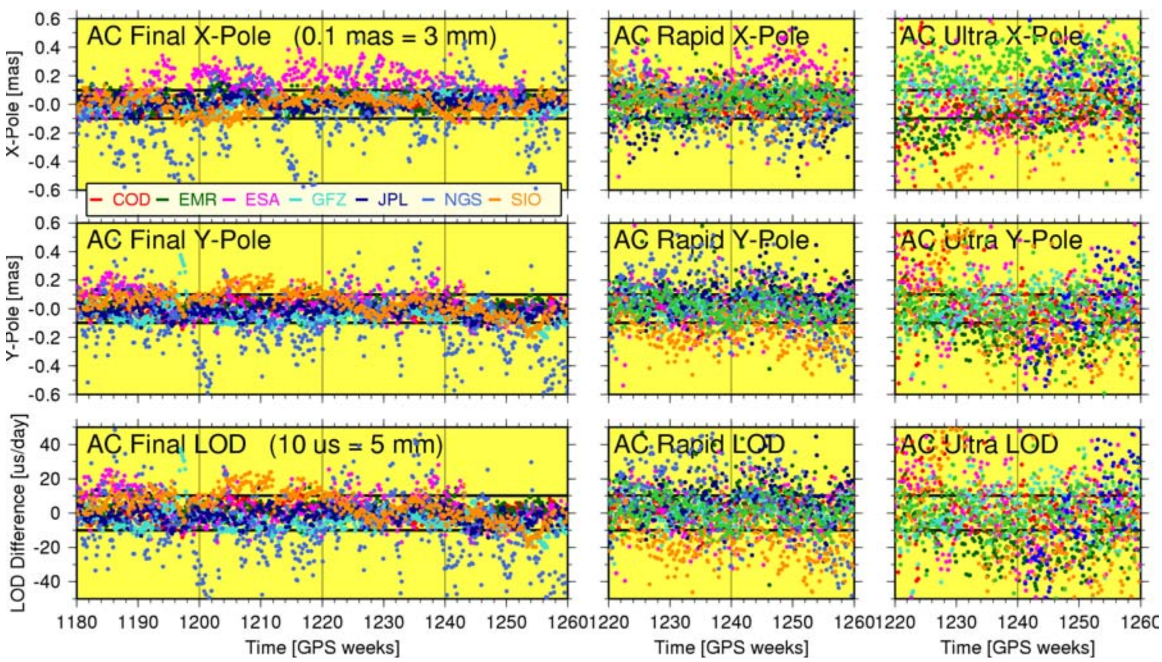

Fig. 4. Differences of individual AC ERP results to combined ERP for IGS Final, Rapid and Ultra Rapid

recently more than half of the satellites were predicted with an accuracy of 4 cm or better, and only a few are worse than 20 cm (Fig.3, middle). An important goal is also that the complete set of satellites is included in the product. Recently often no or only one satellite is missing (Fig.3, bottom).

As another example the consistency of the ERPs is shown in Figure 4. For the Final ERPs the consistency between all ACs is at a level of 0.1 mas for the pole coordinates and 10 µs for the LOD (after correcting a mean-term AC bias). The consistency for the Rapid ERPs is nearly at the same level and even for the Ultra Rapids it is worse by a factor of two to three only.

2 Product consistency

The consistency between the various IGS products is a first measure of the quality, accuracy and integrity gained.

The consistency is immediately checked during the combination between all AC submissions for the same product and is included in the report generated for each combination. This way the quality for orbits, ERPs and clocks are assessed directly. Additionally, the consistency between the products of the various product lines (Final, Rapid, Ultra Rapid) and between different products, like orbits and ERPs, is checked. For example, the orbit rotation between each AC and the combined orbit should agree with the corresponding differences in the ERPs. In Figure 7 (top) both time series are compared for all ACs over the last three years for the Rapid product (GPS week 1100 = Feb 2001, 1260=Feb 2004). The weekly means show a good agreement, and also the daily scatter is for most ACs small. If one looks into the zoom one realizes that even for the higher daily scatter the consistency is kept. The overall scatter reveals the fluctuations in the realization of the RF at each AC. Even for the Ultra Rapid products (Fig. 7, bottom) this consistency is quite good and has significantly improved during the last 6 month. The summary statistics for the "orbit/ERP agreement" is given in Figure 5. The consistency for most ACs is better than 0.1 mas (corresponds to 1 cm in orbit) for Finals and Rapids, and even for the Ultra Rapids a similar high consistency could be obtained. It should be noted that the highest consistency is reached for the Rapid products. The reason for that is the straightforward procedure applied for its generation, whereas for the Finals the ACs are using back-substitution procedures, comprised of several steps.

Consistency checks could also be performed between orbits and station coordinates, i.e. check of the RF realization for both

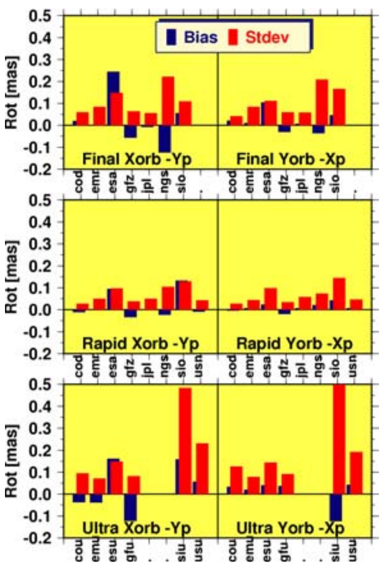

Fig.5. Statistics of the consistency between orbits and ERPs for all products lines. Difference [ORB_{AC}-ORB_{COMB}] - [ERP_{AC} – ERP_{COMB}] is plotted.

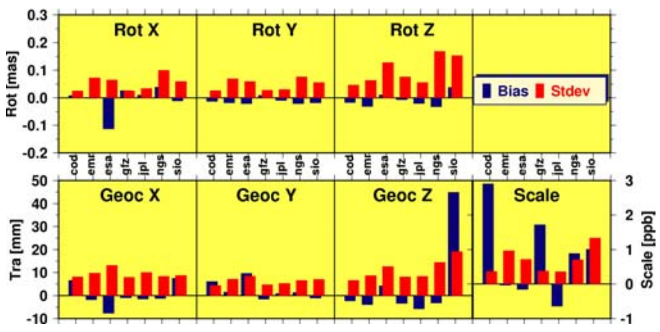

Fig. 6. Comparison of the Helmert transformation parameters between Final orbits and SINEX station coordinates. Difference [ORB_{AC} to ORB_{COMB}] - [SNX_{AC} to SNX_{COMB}] is plotted. (Rem.; SNX_{COMB} is corrected for CoM)

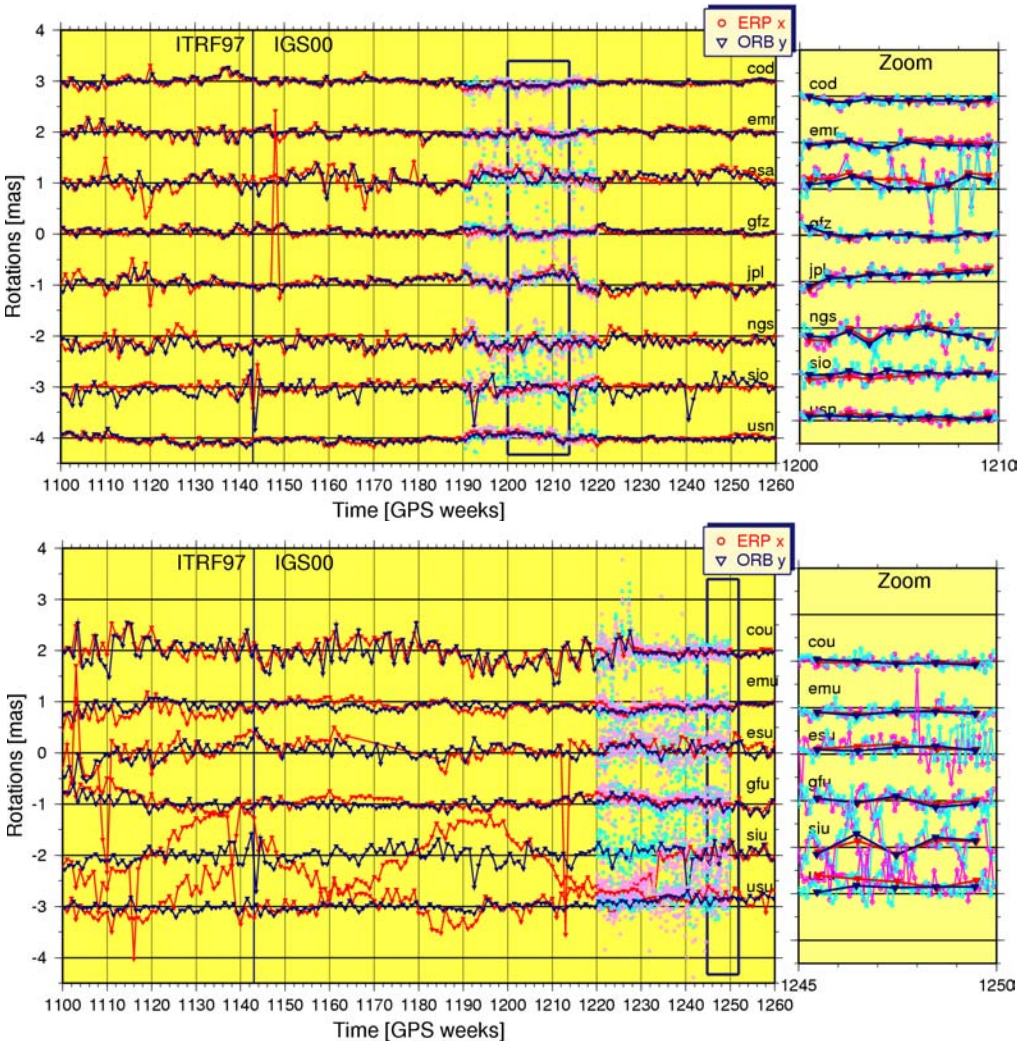

Fig. 7. Consistency between orbits (ORB_{AC}-ORB_{COMB}) and ERPs ($ERP_{AC} – ERP_{COMB}$) for Rapid (top) and Ultra Rapid (bottom) products. Shown are the weekly means and the daily values for selected windows (Rapid:1190-1220;Ultra Rapid: 1220-1230). Additionally, the daily values are zoomed in the right plots for the marked boxes.

products. In Figure 6 compares the Helmert transformation parameters between each single AC's product and the combined product for orbits and for SINEX station solutions. Here the station coordinates in the center of mass (CoM) are considered to be compatible with the orbits, which are in any case computed in CoM. The agreement in the rotational parameters is of the level of 0.1 mas, for the z-rotation, as expected, slightly larger than for the other components. The bias is in most cases even smaller. For the geocenter parameters the bias and the scatter are at the level of 10 mm, only in one case a significant bias is seen. The scatter for the scale is within the level of 1 ppb, but for two ACs significant differences in the scale between orbits and station coordinates are seen, which have to be looked at in more details to be clarified.

3 Quality assurance, reliability and integrity

The quality of the IGS products crucially depends on the quality of the IGS network, mainly on the stability of the reference frame (see Ferland et al. 2004, Ray et al. 2004), and on the quality of the submitted products from the contributing ACs, mainly on using best and consistent models for the data analysis. All these aspects are not discussed here. This paper focuses on the product generation itself. To provide reliable products to the user community the following points are important:

a) Avoiding single point of failure for:

RINEX data. First of all the data availability has to be assured. This is achieved by having redundant global data centers (GDC). Important is also that the stations are sending their data in parallel to two different GDCs to make sure the data will be available for the analysis all the time, also in case of GDC breakdowns.

Product generation. The existence of many ACs will assure the product generation in all cases. This is one of the strengths of the IGS.

Product submission. The ACs send their products to the server at the combination center and in addition to a second server, ideally one GDC. This way a fast recovery of all submissions by the combination center is assured in case of problems at the combination center.

Combination. At present, all combinations are running at a single combination center. Even if those centers having implemented some redundancies it is still some kind of single failure (severe breakdown, internet problems, etc.).

b) Assurance of combined product generation:

The combination centers have to assure that the combination will be performed properly and will generate the combined product. For this purpose the software has to account for all possibilities of corrupted inputs, data and format problems, etc. This is in principle a trivial point, but is during the daily work often a source for problems.

c) Assurance of product consistency and quality:

The consistency between the products is not only important within one product line, but also between the various product lines (Final, Rapid, Ultra Rapid). For some products the consistency down to the mm level may be important.

d) Assurance of the long-term stability and the alignment to ITRF

In the following only the point c) will be discussed, and it will be distinguished between 'on-line quality check', performed immediately during the combination, and 'off-line quality check'.

3.1 On-line quality check

During the combination a series of checks is performed, which for all the products follow similar strategies.

The consistency between the AC submissions is tracked to detect and remove bad contributions. Important is the feedback to the ACs to avoid smaller artificial jumps in the combined solution by a changing number of contributing ACs. Although small, the existing biases between the ACs may generate such jumps. As an example, the strategy for the orbit combination is explained in the following:

- Each single AC is checked for single satellite outliers, which needs to be removed. Then the transformation parameters are checked and if problems in the realization of the RF are detected the ACs results are not used at all. The same holds if the total RMS for an AC is not of sufficient quality. For most of the products it a minimum number of contributing ACs is important for a validation of the results. Generally, all the products get error-codes, and if such information cannot be delivered the product is flagged properly.

- For three globally distributed stations the precise navigation solutions, which give a first measure on the orbit and clock quality, is computed. This test is not performed for the Ultra Rapid product, where the predicted satellite clocks have not a sufficient accuracy.
- For the Final products long-orbits over the whole week are computed, which are able to check the continuity of the orbits between the single days. Although the official ERP product is taken from the SINEX combination, the ERPs coming with the orbits are combined and compared with the official product, giving a measure for the stability of the RF realization for the orbits.
- In near future it is planned to perform a static PPP with the combined orbits and satellite clocks to check their quality and the repeatability in the station coordinate solutions. At the same time a measure of the RF realization by using PPP is obtained. The Helmert transformation parameters will be made public so that very demanding users of the IGS products may apply them to their PPP results. In this context it should be mentioned that presently all the IGS orbits are in CoM, whereas the Rapid clocks are in ITRF and the Final clocks in CoM, so that station coordinates from PPP are in ITRF and CoM, respectively. As recommended in Ferland et al. (2004) this slight inconsistency should be solved in near future.

All the results from the on-line quality checks are included in the reports distributed with the IGS products.

3.2 Off-line quality check

A series of checks are performed between the different product lines. The quality of the Rapid products are validated after two weeks with the Final ones, and each day the Rapids are used to check the Ultra Rapids for the last day.

The Final products, using a free network adjustment, are not affected by wrong RF station coordinates (e.g. caused by earth quakes, antenna changes etc.). The Rapid (and Ultra Rapid) products are usually generated with fixed RF stations making them sensitive to RF problems. A comparison of ERPs from both series can therefore easily be used to check the Rapid RF realizations. Looking into its difference (Fig. 8) revealed for instance the effect of fixing wrong station coordinates at FAIR (earth quake) and KOKB (antenna problem) for several weeks. Therefore it is strongly recommended that the ACs should check their constrained stations before or during the product generation. Additionally, after

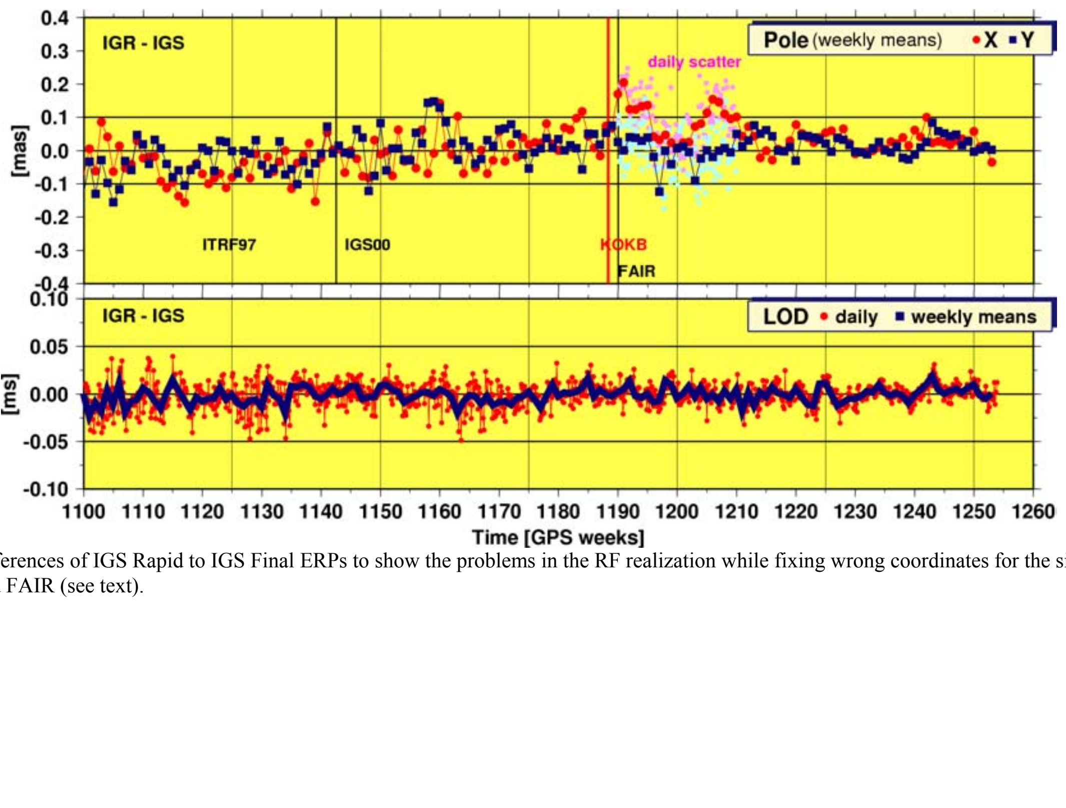

Fig. 8. Differences of IGS Rapid to IGS Final ERPs to show the problems in the RF realization while fixing wrong coordinates for the sites KOKB and FAIR (see text).

the combination a PPP should be used to check the coordinates of all RF stations.

Most critical for the IGS user is the reliability of the predicted orbits. During the combination only the various AC predictions can be considered to compute error codes for the predicted part, and the ACs itself are considering the orbit fits over the observed part for assigning error codes to their individual predictions. If one looks into the errors (compared to the Rapid) of the individual satellite predictions one can easily see that most of them are very well predicted at a level around 5 cm (Fig. 9, top), but also outlier occur from time to time. Some prediction problems are connected with the eclipse seasons (compare Fig. 9, middle). Most of those effects are already well included in the error codes as one can see from the comparison of the RMS and WRMS values in Figure 9 (bottom), but here one detects outliers too. The general problem of any orbit prediction is that one has no correct information on upcoming maneuvers. Also the behavior of rather bad performing satellites can never be sufficiently well predicted. There is no solution within the existing approach. The only solution is a real-time monitoring of the Ultra Rapid predictions, which should be based on the upcoming IGS real-time network. Such a procedure can at the same time yield precise clocks for the Ultra Rapid products so that they can be used for PPP in near-real time (some minutes delay only).

4 Summary

The IGS products have a quality of the level of cm for orbits and clocks as well as mm for ERPs and station coordinates. Therefore all the checks for consistency and integrity have to be performed for that high level. Of basic and growing importance for all the IGS products is the quality in the long-term stability in the realization of the IGS reference frame as contribution to the ITRF, here the goal should

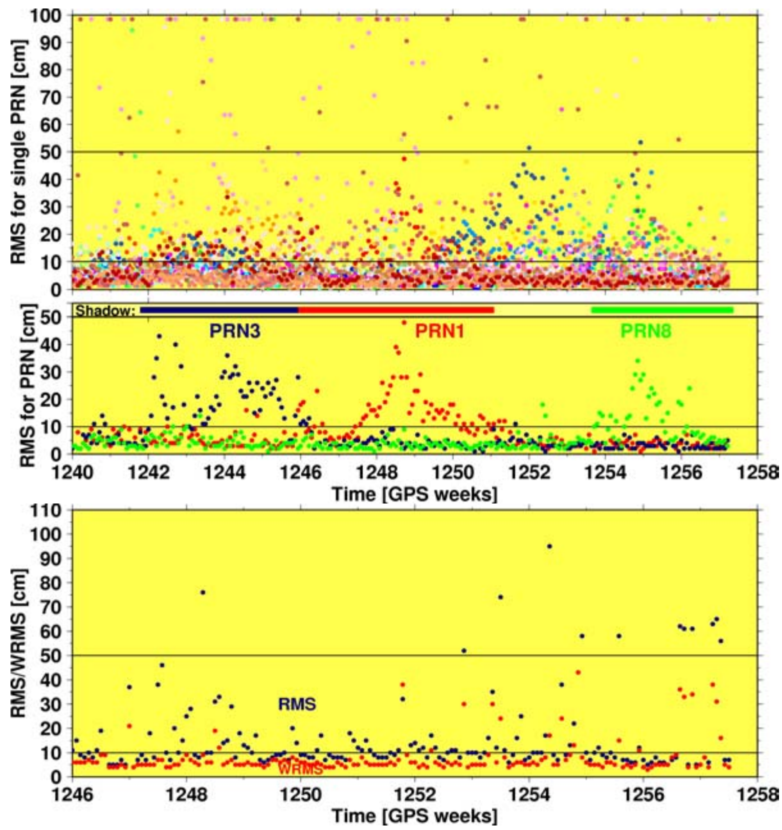

Fig. 9. Individual satellite prediction errors compared to IGS Rapid orbits for selected time interval (top). Examples for eclipsing satellites to show the quality degradation during eclipse (middle). Difference between RMS and WRMS (bottom).

be a mm-level over decades.

IGS products are already checked for internal consistency (1) during its generation and (2) with some delay between different product lines. This has to be improved and more checks should lead to automated warnings and feedbacks. The growing importance of the Ultra Rapid predictions requires better integrity checks, which can only partly be fulfilled within the existing framework. Here a combination with real-time procedures has to be developed.

5 References

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