Moving GPS Precise Orbit Determination Towards Real-Time

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ABSTRACT

A strong interest has been shown by the scientific and high-end user community of the GPS system to have very accurate GPS constellation ephemerides and predictions with very short time delays and with frequent updates. To this end a new product was started by the International GPS Service (IGS) in early 2000 called the Ultra-Rapid product. This paper presents the method and strategy followed to implement this new GPS ephemerides product at the European Space Operations Centre (ESOC), an IGS Analysis Centre (AC) since 1992. Comparisons of results to other IGS products, as well as to other AC's solutions, and to the IGS combined solutions are shown and discussed. Finally some conclusions are drawn with respect to the viability of producing high quality GPS orbits with shorter and shorter latencies.

INTRODUCTION

As proposed in the 1999 IGS Workshop in La Jolla, CA, a new IGS product should be produced by the Analysis Centres (ACs) called the Ultra Rapid orbits (Gendt, et al. 1999). As their name indicate these are GPS satellite orbits produced very soon after the data gathering has elapsed, and they cover an existing gap in the IGS products between the official rapid and predicted orbits. Initially, at least, the product was to contain only orbit information, no clock bias estimations, now that SA has been turned off it has been feasible to develop the satellite clock predictions and include clocks for the entire Ultra-Rapid period, this is currently done by up to 4 IGS Analysis Centres. The orbit files are in the standard sp3 format but contain 48 hours of orbit positions and clock biases instead of the usual 24 hours as for the other IGS products. The first 24 hours are from fitting the data available over the period and the last 24 hours from predicting the solution into the next day.

The Ultra-Rapid orbits contain a fit and a prediction of the GPS satellite orbits, and they reduce the time delay (latency) compared to their traditional counterparts, the *rapid* and *predicted* products. In terms of the orbit prediction the average age moves from 36 to 9 hours, and for the 24 hour fit period the latency moves from 17 to 3 hours.

The second part, which is new, is that the Ultra-Rapid orbits have to be calculated twice a day. The first submission before 03:00 UTC, the second submission before 15:00 UTC. The morning submission incorporates data up to midnight, and the afternoon submission is intended to incorporate the hourly data that has accumulated until 12:00 UTC that day. This new data is used to produce the second Ultra-Rapid submission also with 48 hours of orbit information but starting at noon from the previous day. Therefore there is a sliding window for the Ultra-Rapid orbits of 12 hours instead of the traditional 24 hours.

PROCESSING STRATEGY

The morning and afternoon submissions of the Ultra-Rapid runs at ESOC are calculated for the most part independently of the other products calculated by ESOC and described in (Dow, 1999) (only our *rapid* product results are relied upon for the satellite initial conditions). The morning and afternoon runs are also independent of each other. This way a failure in the sequential execution of one of the days only affects that product and not the others. So, for example, we can continue to submit high quality morning Ultra-Rapid products while the afternoon product may have problems.

The processing strategy is as follows:

1. RINEX data is downloaded and checked for a period covering the 24 hour arc of the orbit to be determined, plus the previous 24 hours (Figure 1). This 48 hour arc of RINEX data is normally used. Data from up to 30 stations are used, depending on data availability from the IGS receiver network.

2. A number of days of Earth fixed positions are also used as observations either from the IGS rapid orbits or from the ESA rapid orbits for the 3 or 4 days before the RINEX data start. These Earth fixed positions of the GPS constellation are used as observations together with the RINEX observations (Figure 1).

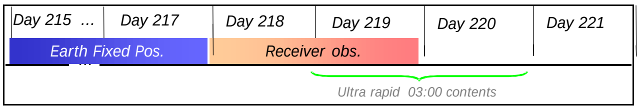

Fig. 1: ESA Ultra rapid solution first step, data types and processing arc.

3. The two frequency RINEX data is combined in a zero difference ionospheric-free combination and antenna phase corrections are applied. The pseudo-range and carrier phase observations are written to an observation file together with the satellite Earth fixed positions, from the previous 3 days as described above.

4. ESA/ESOC's least squares dynamic parameter estimation program, BAHN, is run and the satellite orbits, satellite dynamic models, station positions, satellite and station clock biases and Earth Rotation Parameters (ERP) are estimated. Additional details are given in Romero et al. (2001).

5. The satellite orbit results from the estimation are formatted into Earth fixed positions and used in a second estimation step which fits all of the Earth fixed positions (Figure 2). This second step produces higher quality orbit predictions for the Ultra rapid submission.

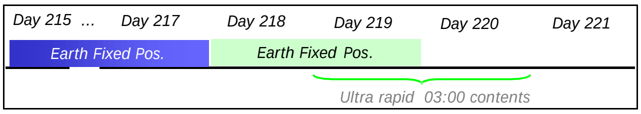

Fig. 2: ESA Ultra rapid solution second step, data types and processing arc.

6. Finally the results are formatted into the appropriate sp3 orbit files, and ERP file spanning the necessary periods, and the satellite exponential correction values are applied. The latter are based on the comparison of the predicted portion of the solution with the propagation from the previous day over that period, and also taking into account the convergence of each satellite's individual solution.

It is worth commenting on the quantities that are estimated in step 4. The list is as indicated above but with the following remarks: The satellite initial conditions are estimated and the orbits are fitted over the entire period of observations (5 days), and a further day of orbits is predicted. The solution is a best fit over the entire arc period using both kinds of data (positions and receiver observations) in the two estimation steps as explained above.

The ERPs are fixed for the period using Earth fixed positions, and usually modelled as linear functions for the 48 hour arc of RINEX data and for the propagated day, initialised with the erp rapid service values from IERS. Over the first four days of the arc the ERPs are fixed to the values associated with each of the Earth fixed position files used.

The satellite and station clock biases are calculated, as they are indispensable when processing zero difference observations. The station coordinates are estimated for the entire arc using an apriori standard deviation of $3x10^{-6}$ km for each cartesian component, in the case of stations belonging to the IGS core, and $5x10^{-1}$ km for other stations outside the IGS core network. The stations normally available for the Ultra rapid processing are those stations submitting hourly files to the IGS with good latencies (less than one hour), an example of the station distribution normally used is in Figure 3. The stations used are marked with green dots and names in bold font.

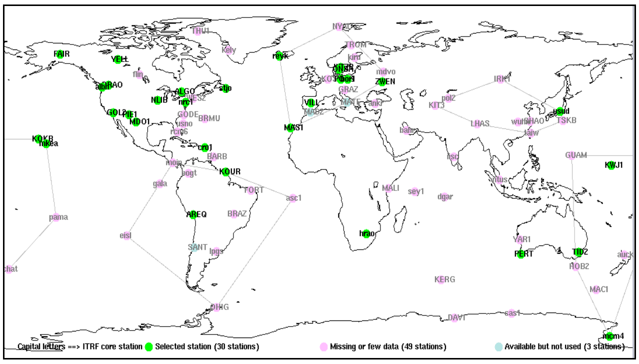

Fig. 3: ESA Ultra rapid station distribution.

The satellite dynamic models in the estimation step calculate a solar radiation pressure coefficient, and a y-bias coefficient, as well as an empirical radial acceleration per revolution for each satellite. The system also estimates each satellite's station keeping manoeuvre as announced in the corresponding NANU (Notice Advisory to NAVSTAR Users), as long as the manoeuvre is contained within the dates for which RINEX data is used in the Ultra-Rapid process. These manoeuvres are carried out for each GPS satellite about once a year to maintain their 12 hour orbit period. Finally since GPS week 1076 small delta-v manoeuvres are estimated at the exit of each satellite from eclipse to try to model the effect on the orbit of the satellite's sun re-acquisition.

RESULTS

On March 3rd, 2000 ESA/ESOC started submissions of the Ultra-Rapid product to the IGS AC coordinator at AIUB. A few weeks later (GPS week 1052) the first combination and comparison results started to appear which combined each centre's solution into an IGS Ultra-Rapid product and then compared each centre's solution to the combination. These comparisons and combinations continue and they provide, among other things, a 3D total rms value over the entire 48 hours contained in the Ultra-Rapid submission, and for all of the GPS satellites. These results can be seen in Figure 4. The total rms error values from all the ACs have reduced to a daily level of between 20 to 40 cm against the combined product.

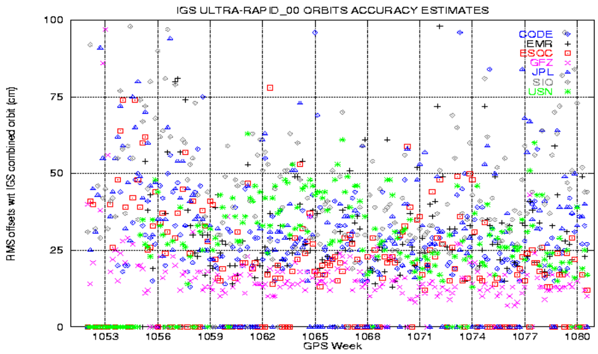

Fig. 4: Ultra-Rapid RMS error of individual Analysis Centre solutions versus the combination

The overall total rms error values over the entire result period can be deceiving since there is a fitted portion and a predicted portion in the submitted results of each Analysis Centre. Therefore epoch by epoch comparisons to the combined product have been produced to determine the behaviour of the satellite orbit calculations over the entire 48-hour arc. Figure 5 shows the comparisons over the entire Ultra-Rapid submitted arc for a typical of day versus the combined product (IGU).

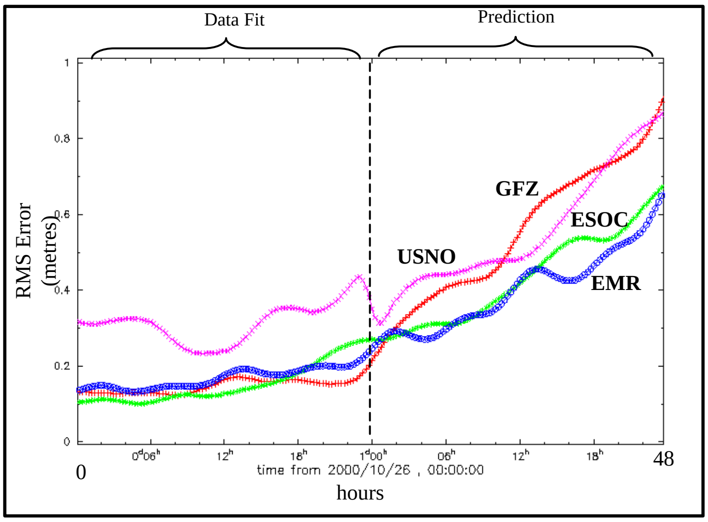

Fig. 5: ACs' Ultra-Rapid vs. the IGU combination RMS of errors for each epoch of one day's solution.

A close look of these results shows over time that the fitted part of the orbit solutions from both centres are in good agreement with the combination, and that the disagreements in the solution for the entire arc lie in the predicted part of the orbits. An important thing to be noticed is the fact that the orbit predictions degrade mainly linearly in time. The predicted part of the Ultra Rapid arc can be compared to the estimated orbits produced the following day and the comparisons of both solutions produces the results shown in Figure 6.

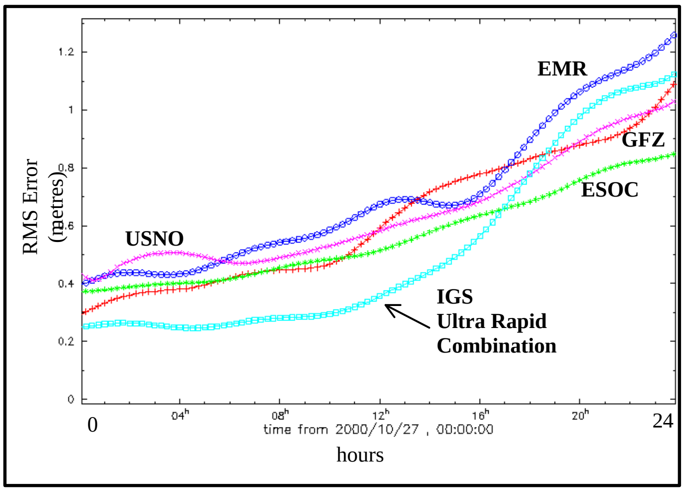

Fig. 6: Ultra-Rapid orbit prediction arc vs. IGS Rapid RMS of errors for each epoch of one day's solution

Figure 6 shows the RMS of the errors for the entire GPS constellation of the orbit prediction arc of the Ultra Rapid (IGS combination and individual AC solutions) versus the IGS Rapid orbits calculated 38 hours later. All of the predictions' errors can be seen to increase linearly as time goes on.

SATELLITE CLOCK BIASES

Recently the satellite clock biases have started to be a part of the ESOC Ultra rapid submission. The satellite clock bias for each of the GPS satellites is an important quantity which comes out of the POD process and they characterise the bias and the drift in the on-board oscillator for each of the GPS satellites versus a quasi-continuous time scale. The values range over several hundred microseconds across the GPS constellation.

As discussed above the clock biases are calculated in the POD process described above but they had not been sent out until recently since they were assumed not to be predictable like the satellite orbits are. This was the case when Selective Availability was turned on previous to last year, but since it has been switched off more interest has been expressed in including estimated and predicted clock biases in the Ultra rapid products together with the orbits.

Currently the clocks are predicted at ESOC by post processing the results of the least squares estimator and fitting a simple curve for each of the satellites. If this curve satisfies a convergence criterion in a least squares sense then the clock for the entire 48 hour arc is sent out. If for some reason the clock values estimated cannot be fitted then no clock is provided for the satellite. It is assumed in this case that the clock bias estimated are not of good enough quality either because of mismodelling, bad observability of the satellite or bad behaviour at the reference station.

The function currently used to fit the satellite clock biases for their prediction into the future is a simple bias plus drift plus sinusoidal term. This function fits the satellite clocks to better than 2 nanoseconds most of the time, as long as there were not any of the problems with the reference station.

Comparison between the predicted clocks with the actual values later estimated shows their agreement to be around 3 to 5 nanoseconds over the entire GPS constellation. This activity is currently pursued by up to 4 IGS Analysis Centres. Figure 7 shows the satellite clock bias epoch by epoch for GPS satellite PRN02 (sv-13) after the values are estimated and before they are included in the sp3 file. This satellite contains an on-board Cesium atomic oscillator. No relativistic correction has yet been applied at this point to the satellite clock biases.

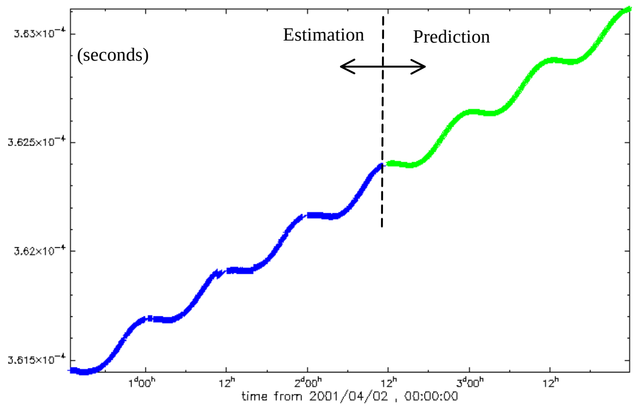

Fig. 7: PRN 02 Satellite clock bias estimated and predicted (vertical scale ranges from 361.5 to 363.1 µs)

Figure 8 shows the satellite clock bias epoch by epoch for GPS satellite PRN07 (sv-37) after the parameter estimation step. This satellite contains an on-board Rubidium atomic oscillator.

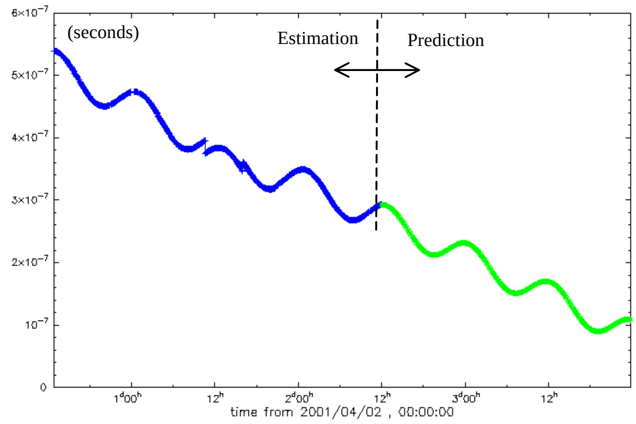

Fig. 7: PRN 07 Satellite clock bias estimated and predicted (vertical scale ranges from 0 to 0.6 µs)

Figure 8 shows a discontinuity about half way in the estimated part. This is quite common in satellite clock bias calculations, and is clearly undesirable. The inconsistency mainly reflects a slight jump in the station selected as reference, bad observability for that satellite over that time, or few stations observing the satellite.

CONCLUSIONS

Ultra-Rapid processing has been successfully implemented at ESOC with very positive results. It can be concluded that the prediction of the GPS satellite orbits can be difficult in terms of agreement between ACs and agreement to the orbits later observed. Also, the early results from the satellite clock bias estimation and prediction within the Ultra rapid product show good comparisons with the other Analysis Centres involved in this activity, and 3 to 5 ns agreement to the observed satellite clock biases.

Finally it is worth remarking that due to the successful implementation of this product within the IGS the traditional *predicted* product has been discontinued since GPS week 1105 (March 2001). It can also be foreseen that the *rapid* product will also be discontinued once the quality of the estimated orbits within the Ultra rapid product reaches similar performance.

REFERENCES

Dow, J., Martin-Mur, T.J., ESA/ESOC Processing Strategy Summary, *IGS Central Bureau web site*, igscb.jpl.nasa.gov/igscb/center/analysis/esa.acn, 1999.

Romero, I., Garcia, C., Dow, J., Zandbergen, R., GLONASS Precise Orbit Determination, *GNSS 2001 Proceedings*, Seville, May 2001.

Gendt, G. et al., Regarding IGS Near real-Time Products and their Applications, IGS Analysis Centre Workshop Proceedings, La Jolla, 1999.