Ultra-rapids and ultra-rapids predictions for GPS

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1. Role of the ultra-rapids

Moving the precise GPS analysis and its applications into real-time, the demand on available high quality GPS orbits is growing. In April 2000, sub-daily combined orbit product has been provided by the IGS – the ultra-rapids generated twice a day [Springer and Hugentobler, 2001]. Before the ultra-rapids, the IGS predicted orbits (for 24-48 hours) were ready by IGS for the real-time application. The ultra-rapid product was enabled in March 2000 thanks to the contribution from four IGS analysis centers (GFZ, EMR, SIO, JPL and early followed by all others) and because a sufficient data of IGS global network was provided in hourly files, though not yet perfectly distributed over the globe.
The ultra-rapids were initiated especially on demands of growing number of near real-time GPS analyses for meteorology applications (i.e. the estimation of troposphere parameters for improvements of weather prediction). The use of this product reduced necessary prediction of the orbits below 15 hours (9 hours in average) and significantly improved and simplified any near-real time analysis. The analyses could already use fixed orbits. The ultra-rapid product thus proved from the very beginning its usefulness at least for the estimation of troposphere parameters in near real-time [Douša, 2001a].
Nevertheless, some problems related to the ultra-rapids remained. They mostly consisted in hourly data support, its global coverage, missing satellites, low redundancy of individual solutions for the combinations etc.

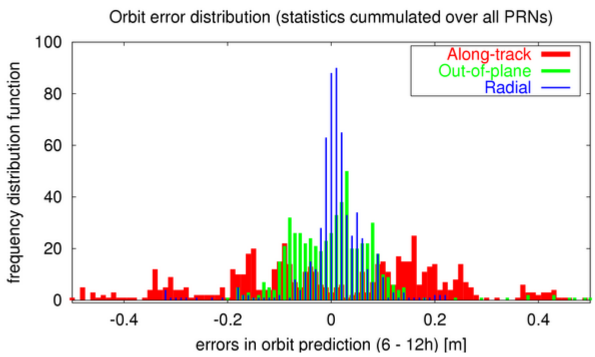

Fig. 1 *Component orbit error distribution for the ultra-rapid predictions (2002)*

1.1 Demands and motivations

The distribution of the errors in orbit positions (radial, along-track and out-of-plane) of the ultra-rapid predicted portion is given in Fig. 1. The radial component is clearly the most accurate while the distribution of along-track errors is very scattered. The along-track accuracy is the most rapidly decreasing when extending the orbit predictions, which is a case in Fig 1 with prediction up to 12 hours.
For estimation of standard troposphere parameters [zenith total delays, ZTD] in (near) real-time, the classical 'network' approach or Precise Point Positioning (PPP) method [Zumberge et al., 1997] could be used. Provided mostly on regional scale and using a simple strategy, both approaches fix the actual precise positions of the receivers and satellites. The main difference remains only in utilizing the raw GPS observations – double-differences in 'network' approach or zero-differences in the PPP. Differencing the observations significantly eliminates some errors, especially the receiver and satellite

clocks, but particularly errors in the orbit positions as well. While PPP technique is highly dependent on radial component (demands are on centimeter accuracy), the network – baseline – solution depends on the individual baseline length and its orientation with respect to the errors in the orbits. Figures 2 and 3 demonstrate the impact of the error induced separately into a single GPS orbit for all three components (radial, along-track and out-of-plane). The ZTD solution was then compared to that of using the original final IGS precise product. The ambiguities were resolved to integer values only with the original orbits and they were simply fixed in the simulated (corrupted) solution. In the alternative solution, we solved also for the float ambiguities to demonstrate a high potential of the errors in orbits to be absorbed by float ambiguity estimation, compare left and right plots in Fig. 2.

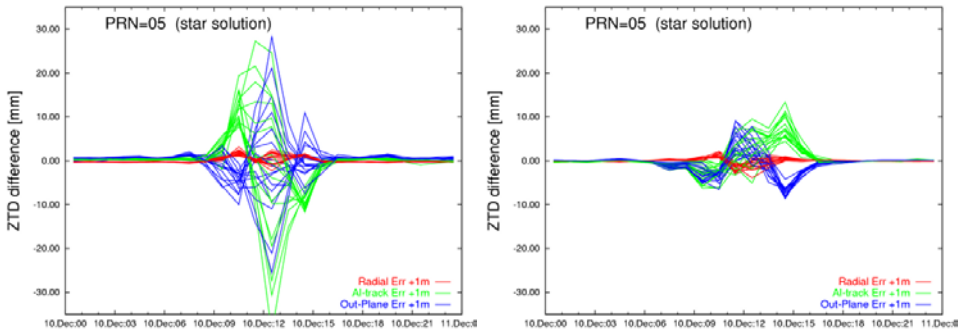

Fig. 2 *Impact of single orbit systematic errors (1m) on ZTD based on the 'network' approach. Left - ambiguity fixed solution, right – ambiguity free solution. The ZTD from simulated orbit-error solution are compared to the solution with the original IGS final orbits.*

These figures show also the individual site ZTD responses to the simulated error. The radial error in the network solution is significantly eliminated, but it is not true in case of the other error components. For given geometry, the ZTD bias is proportional to the size of the error in orbits. The demands for the accuracy of the orbits are thus at some centimeters level for all components – when applying PPP or the 'network' near real-time ZTD estimation.

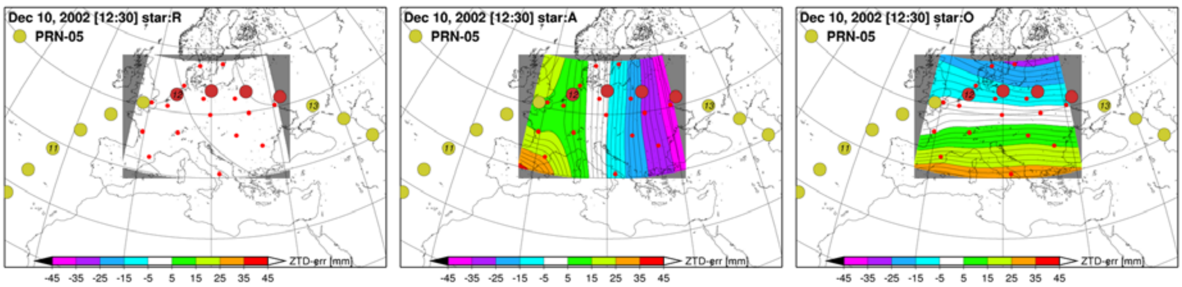

Fig. 3 *Simulated orbit component error (1m) for ZTDs estimated in the 'network' solution. The satellite PRN5 orbit was only shifted (yellow points show 15min satellite track, red points marks the actual one-hour position). The ground network is plotted with small red dots; the baselines were created using a central station.*

The demands for the IGS precise orbit products are basically three-fold: the accuracy, the timeliness and the completeness. Not all attributes could be satisfied simultaneously and more products were thus provided by the IGS. While the original IGS final orbits aimed for the highest accuracy (and completeness), the IGS rapids pushed the accuracy and completeness to the very reasonable timeliness. The same aim was followed when introducing the IGS ultra-rapids but using the priority on the timeliness. At first, the new ultra-rapid product has replaced the IGS predicted orbits. Appropriate accuracy and completeness improvements in the ultra-rapids could lead up to the substituting also the IGS rapid product. To reach this task in future, the ultra-rapids were well designed from its beginning

– the product contains consistent 1-day fitted portion and 1-day prediction enabling a smooth transition from the post-processing to the (near) real-time.

Table 1 *Summary of the basic contemporary product features and actual ability for providing them. The products are ordered with respect to the highest accuracy and the timeliness demands. The emphasize fields are accounted for (near) real-time features.*

	Finals	Rapids	Ultra-rapids	(Predicted)	(Real-time)
applications	best post-processing	rapid post-processing	rapid post-processing, ***(near) real-time***	***(near) real-time***	***(near) real-time***
product	fitted	fitted	fitted + ***predicted***	***predicted***	***fitted + predicted***
data flow	daily	daily	daily, ***hourly, RT***	daily	***real-time***
latency & upd.cycle	12 days daily	17 hours daily	***3 hours sub-daily***	17 hours daily	***x-sec/min x-sec/min***
necessary prediction	-	-	***+ 15 hours***	***+ 48 hours***	***x-min/hours***
available network	complete IGS	complete IGS	***limited (hourly)*** complete (daily)	complete IGS	***limited (real-time)***
operation	interaction possible	interaction possible	***full-automated***	interaction possible	***full-automated***

1.2 Special features of the ultra-rapids

Table 1 compares various product inputs, analysis methods and other general features. The predicted and real-time products are included for the completeness in the comparison, though there are actually not provided within the IGS (even the latter could be in principle considered for the future). The table demonstrates special features of the ultra-rapid orbits, which could be summarized as follows:

1. The product is aimed for the fitted as well as predicted portions. This basic feature helps to accommodate a wide-spectrum of applications.
2. Combination could include different analysis strategies. This reduces common instabilities (e.g. due to near real-time data, etc.) and improves the robustness of the product. The individual analysis strategy can be as follows:
   - x-hour/day sliding window
   - x-hour batch processing with sub-daily NEQ stacking
   - rapid solution updated by the sub-daily NEQ pre-processing and stacking
   - previous precise orbits refined with near real-time data
   - full real-time derived solution etc.
3. The product is strongly dependent on hourly/real-time data flow and data distribution. The most current problems still remain in lack of the optimal data. The importance of redundant and independent data is absolutely necessary.
4. The product is based on full-automated operation mode. High individual robustness and redundancy within the combination is required. The integrated monitoring should be incorporated into the product generation to assist the users.

1.3 IGS ultra-rapids monitoring

Extensively using the IGS ultra-rapid orbits from its beginning, we were motivated to continuously monitor this newest product. Our orbit monitoring is based on the comparisons of ultra-rapids with respect to IGS rapid and final orbits. For better evaluation, the predicted portion is split into four 6-hour periods. Figures 4 shows the whole history of the product quality and its continuous

improvement. During the first two years, the quality performance of the ultra-rapids was not homogeneous for all the available satellites. In 2002, the solution was stabilized, but as obvious from Fig. 5, the significant number of satellites (up to six) was missing during the first half of 2002, which was the reason for visually better consistency of the official combined orbits.
The clearest improvement is evident for the second half of 2003, especially for the predicted portion. At that time the contribution from CODE was included. The CODE is fitting the predictions from the rapid orbits with a new near real-time data. The combined IGS ultra-rapids thus profits from very well predicted product based on complete IGS network and daily data too.

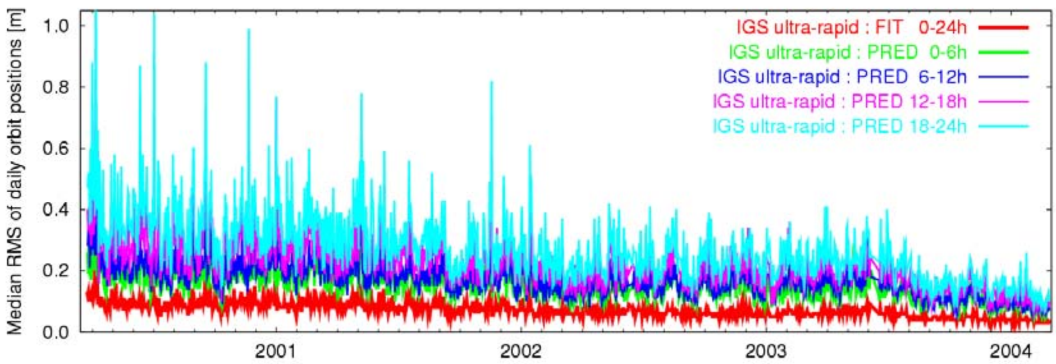

Fig. 4 *History of qouality improvements of the IGS ultra-rapids for fitting and predicted portions.*

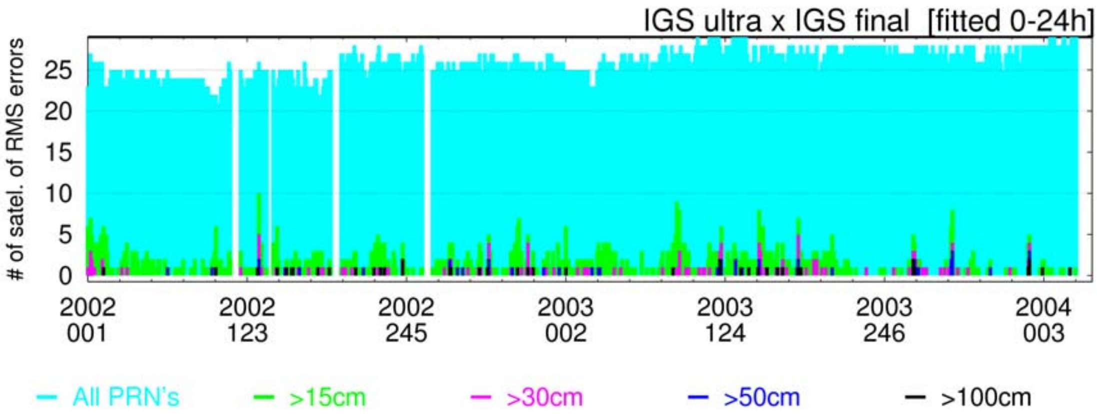

Fig. 5 *Quality and completeness evaluation of IGS ultra-rapid orbits with respect to the finals.*

2. Ultra-rapid orbits from GOP

The Geodetic observatory Pecný (GOP) has started the near real-time global processing for orbit determination in 1999, [Douša, 2001b]. The first developments aimed to the efficient hourly orbit product, but the update rate was later reduced to 3 hours using analysis with better orbit predictions. The system was designed as robust, but extremely efficient. The Bernese GPS software (Bernese) [Hugentobler et al., 2001] and the Bernese Processing Engine are used supported with a special developed system of perl-scripts.

2.1 Processing robustness and efficiency

The robustness is achieved through many internal control procedures with iterative steps, a self-initializing mechanism and finally, with an independency on external information (satellite manoeuvres, a priori precise orbit positions or other supporting products). Only GPS hourly observation and navigation files are thus necessary for the analysis.

The high efficiency of the solution is possible due to a low level redundancy in the processing. It is achieved by nearly un-redundant processing strategy, based purely on 6 hours pre-processed data batches. These are stored in the normal equation files (NEQ) and combined later into a multi-day solution convenient for the precise orbit determination. Redundancy in the processing thus remains in update rate bellow six hours only (actually three hours), when more series of NEQs are generated. This redundancy is exploited for the solution consistency monitoring.
Further improvements in the efficiency could be achieved by reducing two iterative steps for data pre-analysis. Nevertheless, we protect both steps in favor of high robustness.

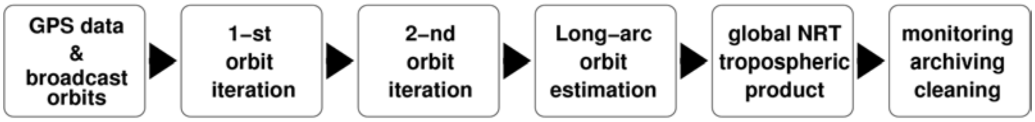

Fig. 6 *Sequential processing blocks.*

2.2 Speedup using a parallel processing

The basic sequential top-level approach is clear from Fig 6. The first and last blocks are devoted to the data input and the product output, which are provided through the GOP data center and web-based monitoring scheme. The improvements of a priori orbits (on daily basis) and data pre-analysis (6-hour batches) are performed in two iterations within the second and third sequential step. The following block is devoted to the final orbit determination using a multi-day combined solution. This is based on the last and previously pre-processed solutions. Also the orbit quality evaluation is provided within the same block.
An additional analysis for near real-time troposphere delay estimation comes in the last but one step. In this analysis step we use already fixed GOP orbits and we evaluate the orbit product from the application point of view. This part of the analysis could be easily provided also in the higher update rate if required for global near real-time ZTD product exploitations.
Within each of the main single sequential steps, many tasks for parallel processing are available. If they are relevant (in case of multi-processor machine or in cluster of machines), total time of the processing can be significantly reduced. In our solution, the parallelizing model is applied for all tasks concerning the individual data/files manipulation (getting files, file by file transfer etc.) and for all independent steps of the pre-processing including baseline-by-baseline mode analyses. Significant speedup is achieved here using the cluster-based pre-analysis of selected regions of the global network. In this way, the processing is redistributed and combined into a single global solution at the end of each sequential top-level block.

2.3 Pre-processing part

Two iterative steps in the preprocessing are performed for higher solution stability. Both contain the standard analysis steps coming after the data are converted into Bernese internal data format. Single point positioning using the zero-difference code measurements is applied for synchronization of the satellite clocks only. The single-difference observations are generated for baselines and saved in the individual files. Mostly the baselines are created with respect to the regional cluster definitions maximizing the number of observations for pairs of stations. In case of ZTD estimation, the network is design as global with a strategy according to the shortest baselines with additional conditions for maximizing available observations. The double-difference observations are always created temporarily during the least-square estimation. The data cleaning (cycle slip detection, new ambiguity setting etc.), outlier rejections, site-wise and satellite-wise quality checking are applied in limited iterative loop if necessary. Ambiguities are currently estimated as the float numbers and pre-eliminated before solving for the normal equations.
Improved a priori daily orbits and the normal equations (NEQ) of the global solution are the results from both pre-processing steps. The NEQs are stored in binary Bernese internal format and they are used in all relevant combination steps during all next 72 hours.

2.4 Final combination for the orbits

Long-arc orbit determination [Beutler et al., 1996] consists of the procedure of combining 6-hour normal equations into a three-day global solution, Fig 7. The process is performed iteratively for the appropriate orbit parameterization. Not all the long-arc orbits could be modeled with the single set of the parameters (6 Keplerian and 9 additional radiation pressure parameters, some of which are tightly constrained). There is possibility to split the arc into more pieces (if necessary due to a manoeuver) or include stochastic pulses, which could help to model remaining external forces affecting the satellite motion. The latter are expressed as the small velocity changes at 6-hour arc boundaries of the normal equations.

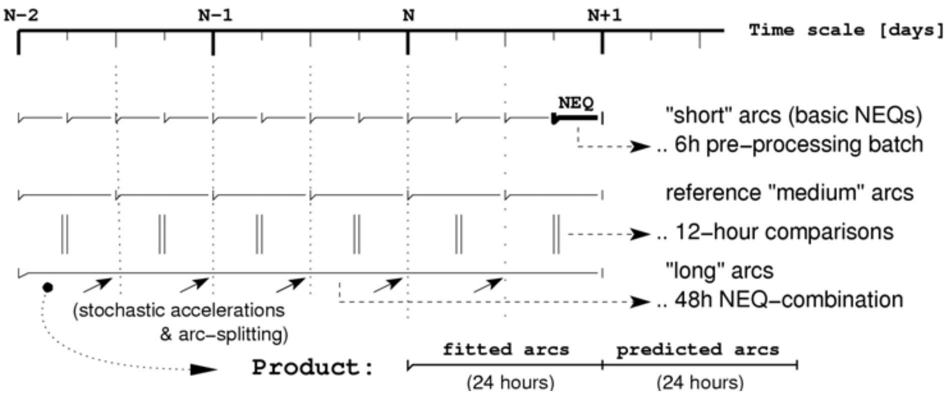

Fig. 7 *Chart of the long-arc orbit combination procedure*

The setup of the final appropriate set of orbital parameters is based on the iterative re-combination of three-day long-arc solution and its comparisons to the "reference" medium-arcs from 12-hour solutions, Fig. 7. At first, medium-arcs (orbits of one satellite revolution approximately) are generated for every two sequential NEQs. They are stored for next days and used as half-day orbits, which are mostly sufficiently handled with a single set of orbital parameters in most cases. The comparison is then performed between the estimated individual long-arc orbits and all corresponding medium-arcs (within their validity periods). Through the analysis of residuals, per satellite and per 12-hour segment, recommendations of actions are generated for the next phase of processing.

If any orbit of a given satellite can not be represented by the original set of parameters, two actions may take place: (i) introducing three stochastic (dynamic) parameters in addition to the original set; (ii) splitting the long-arc and introducing an individual sets of parameters for specific arc segments. This process may need to be iterated two or three times in order to reach the best parameterization. When the above mentioned actions are taken, special rules must apply: (i) splitting is not permitted during the last day since the final orbit product is based on that day; (ii) any split segments have to be a multiple of 12 hours. The stochastic parameters enables to estimate the small velocity changes in radial and along-track components once per revolution (these are loosely constrained), while the out-of-plane component velocity changes are tightly constrained. Since all medium-arc orbits of one revolution are stored, all next iterations consist of the long-arc re-combination followed by the residual analysis until the special recommendations for the next job are requested.

Figure 8 shows an example of the iterative combination technique. Each group of six columns represents a single iteration with residual evaluation for six half-day periods (altogether three days). The final iteration applied additional stochastic parameters for 4 satellites (PRN 2, 15, 17, 21), while two long-arc orbits (PRN 17 and 21) were split into 2 or 3 independent segments due to a long-arc modelling problem. Resulted orbits were significantly improved, especially in the last day (two last single columns), which are definitely used for the official product extraction. It is clear from the example, that the improvements deal with most orbits even though the special modeling was applied for a few of them only.

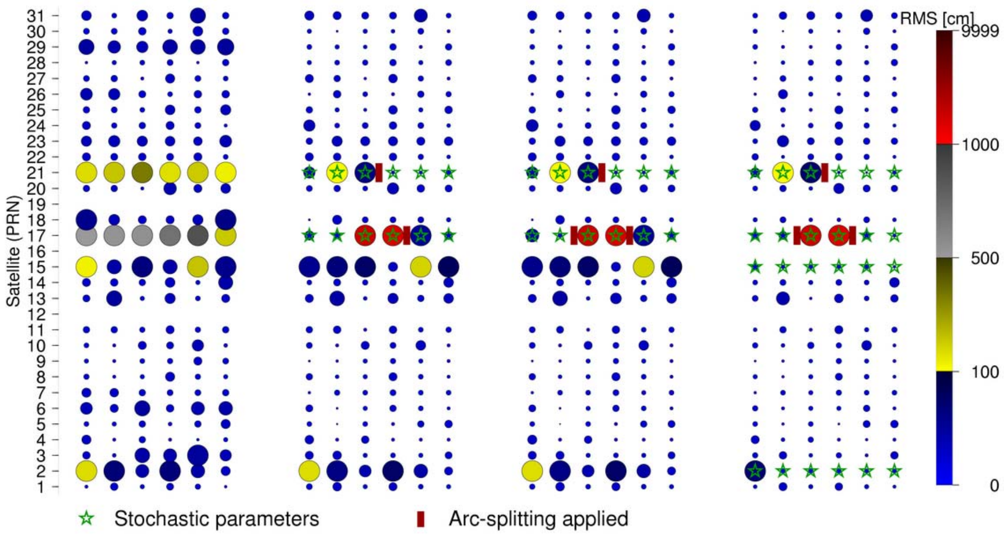

Fig. 8 *Example of handling the orbital parameters in the final long-arc determination.*

2.5 Orbit evaluation and monitoring

The quality monitoring system is an integral part of our global near real-time analysis. The results are evaluated in internal consistency checking between the consequent 3-hour orbit updates. Resulted characteristics from the last comparisons are additionally applied for generating the accuracy code within the product in SP3 exchange format.

The quality of the orbits is also tested by the comparisons to all IGS products in backward. This evaluation is applied for every last solution of each day only (we assume the quality independence on the hour of day) and the statistics are archived.

The differences between GOP and IGS final orbits are at the level of 10-12cm median RMS for the fitted portions and bellow 20cm for the 12-hour predicted portion, Fig. 9.

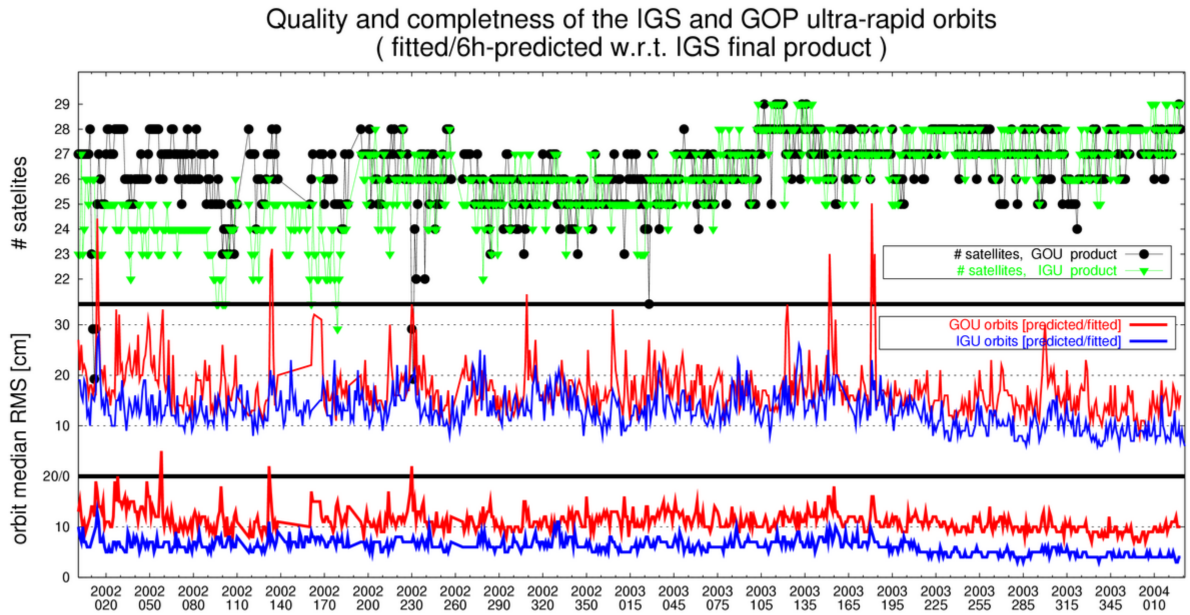

Fig. 9 *Evaluation of GOP and IGS ultra-rapid orbits from period 2002-2003.*

2.6 Further improvements

Actually, we are moving the processing to a new platform with significantly higher performance. The facility of two dual-CPU machines mounted in the single processing cluster is ready. New Bernese Processing Engine (BPE) of the BSW V5.0 is anticipated due to a stable processing in the extensive parallel mode, where the old BPE system is not stable enough.

Development of the better accuracy code is desirable for our solution. Appropriate ambiguity resolution would improve significantly the orbit determination.

When any satellite is not present at the 6-hour solution initializing the long-arc orbits, it is missing also in the final orbits. This occasional technical deficiency should be avoided as well. The manoeuvered or unhealthy satellites would be solved by appropriate weighting rather than excluding them.

Satellite clocks could be estimated whenever a sufficient CPU time will be allocatable. The PPP processing should be then performed for ZTD estimation as part of the integrated monitoring system.

3. Future of ultra-rapids and the GOP contribution

The IGS ultra-rapid orbits are already very important product for a wide spectrum of applications and there is a high potential for its steady use in future. Though the accuracy is already at the level of 10 cm in the sense of weighted RMS, the homogeneity of all predicted orbits are still not optimal and the completeness is sometime not definitely accomplished. With significant improvement in July 2003 (see Fig. 4) the IGS ultra-rapids are very close to bringing the fitted portion into line with the IGS rapids. This is a challenge for potentially smooth incorporation of the rapids into the ultra-rapids before definitively replacing them. Another improvements concerning the predicted portion could be still reached by the increasing update from current 12 hours to six or even three hours.

Because of the strong future of the ultra-rapids, the next developments should be aimed for the integration of all applicable GNSS orbits. To protect or even increase actual diversity in individual solution approaches (based on different data-flow and analysing strategies) should remain the priority for the high product robustness too.

The GOP intentions within the IGS are to contribute with the ultra-rapid solutions, actually precise GPS orbits, in future GNSS orbits. We are able to support updates of orbits at the rates of 6 or 3 hours.

Acknowledgements

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