IGS Ultra rapid products for (near-) real-time applications

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Camera-ready Copy for

Physics and Chemistry of the Earth

Manuscript-No. ???

Pergamon

Phys. Chem. Earth, Vol. *, No. *, pp. 101–105, 20**

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Received: ??? – Accepted: ???

Abstract. Since GPS week 1052, 5 March 2000, the IGS is producing a new combined orbit called the IGS Ultra rapid product, IGU. The combined IGS Ultra rapid products are being made available twice every day, at 3:00 and 15:00 UTC, with a delay of 3 hours after the end of the included data interval, and are based on solutions from up to seven different IGS Analysis Centers. The main reason for the generation of the Ultra rapid products are the requirements, in both timeliness and accuracy, for near-real-time atmospheric monitoring, e.g., weather predictions. Each ultra rapid orbit file covers 48 hours. The first 24 hours of the orbit are based on actual GPS observations (real orbit), the second 24 hours are extrapolated (predicted orbit). Like the IGS Predicted (IGP) orbits, the Ultra rapid orbits are available for real-time usage. However, the quality of the Ultra rapid orbits should be significantly better because the average age of the predictions is reduced from 36 hours (IGP) to 9 hours (IGU). When the quality of the IGU products reaches a satisfactory level the IGU products will replace the IGP products.

We will demonstrate that the accuracy of the IGS Ultra rapid orbits is at the 30 cm level, in a weighted RMS sense, which is significantly better than the 70 cm accuracy of the IGS Predicted orbits. We will also demonstrate that with this orbit quality it is possible to derive tropospheric zenith path delay estimates with a precision of 7 mm, which corresponds to approximately 1 mm precipitable water vapor. This level of precision is only achieved when "bad" satellite predictions are (automatically) detected and handled.

1 Introduction

The number of real-time (RT) and near-real-time (NRT) applications of GPS are steadily growing. At present the most important application the IGS has to be prepared for is the tropospheric and ionospheric monitoring from both ground-based and space-based GPS receivers. In preparing the near-real-time monitoring the global tracking network has partly switched from a daily data retrieval to an hourly retrieval interval. For the near future the generation of global (IGS) products may be based on these hourly data retrievals. This will allow for much faster IGS products.

During the 1999 IGS Analysis Center workshop, which took place in June 1999 at the Scripps Institution of Oceanography in La Jolla, California, the position paper "Moving IGS products towards real-time" by Gerd Gendt, Peng Fang, and Jim Zumberge, proposed the generation of both more rapid and frequent IGS products for (near) real-time usage. These products, which will be delivered every 12 hours (two times per day), will contain a 48 hour orbit arc from which 24 hours are real orbit estimates and 24 hours are orbit predictions. The latency of these products is 3 hours, which means that the predictions will have an average age of only 9 hours. Like the IGS Predicted orbits (IGP) these "Ultra rapid" products are available for real-time usage, but their quality should be significantly better because the average age of the predictions is reduced from 36 to 9 hours. The first Analysis Center ultra rapid solutions were provided by GFZ by the end of October 1999. The generation of a combined IGS Ultra rapid product (IGU) started in March 2000 based on contributions from up-to five different Analysis Centers. Within a few weeks seven analysis centers were contributing to the IGU products on a regular basis.

We will discuss first results of the IGS Ultra rapid combinations. By comparing the IGU product to the other IGS products we will demonstrate the quality of this new product. In particular we will compare its quality to the IGP (predicted) product. Besides these comparisons we will also use the different IGS combined orbit products to process a small GPS network and compare the obtained results. The focus will be on the differences in the tropospheric zenith delay estimates because these are the parameters which are the "driving force" behind the IGS Ultra rapid products. In addition we address the important issue of detecting and handling satellite modeling problems. Based on the comparisons of the IGS Predicted products with the IGS Rapid (IGR) products the quality of the IGP products is estimated to be at the 70 cm level in a weighted RMS (WRMS) sense. Because of the much reduced prediction "age" the quality of the IGU products is expected to be well below the 70 cm level.

2 Quality Assessment of the Ultra rapid products

In this section we will try to asses the quality of the IGS Ultra rapid products. For this purpose we use the results coming from the routinely performed ultra rapid orbit combination and the rapid orbit comparison. For the generation of the IGU products the orbits and corresponding Earth Rotation Parameters (ERPs) coming from the individual IGS Analysis Centers (ACs) are combined. This combination serves two purposes. First, it provides very valuable feedback to the ACs about the quality of their solutions compared to the solutions of the other ACs. Secondly, the resulting combined solution constitutes the official IGS product. Thanks to having several ACs, giving a manifold redundancy, the quality and the reliability of the IGS combined products is very high.

For the real orbit estimates like, e.g., the IGS Final and Rapid products, the orbit combinations give very realistic numbers in terms of quality. For the predicted orbits there are several occasions were the ACs make similar errors. In those case the combined solution may look very good but actually contains a few "bad" satellites. For this purpose the IGS Predicted products are compared to the IGS Rapid products as soon as they become available (17:00 UTC). This gives a more realistic figure of the quality of the predicted orbits. For the same reason the IGS Ultra rapid products are also compared to the IGS Rapid products.

Besides using the information coming from the routine IGS combinations and comparisons we will also use the IGS Ultra rapid products to process some GPS data. For this purpose we have selected a small network of three stations which are separated by 400 to 600 km. This network we will process with all the different IGS products: Final, Rapid, Predicted, and Ultra rapid. Because the major interest in Ultra rapid products comes from meteorology we will focus on the tropospheric zenith delay estimates from this network.

2.1 IGS Combinations and Comparisons

Twice every day the Ultra rapid solutions from the different ACs are combined. These combinations are performed at 2:55 and 14:55 UTC to insure that the IGS products are available at 3:00 and 15:00 UTC, respectively. All AC solutions submitted until that time are used in the combination. The orbit combination automatically detects bad satellites from individual ACs, using a 5 sigma threshold, and removes them from the combination. All accepted solutions are combined in a two step procedure. The first step is used to determine the weights for the individual analysis centers. In the second step these weights are used to give the actual combined orbit (Springer and Beutler, 1993; Beutler et al., 1993; Kouba, 1999; Kouba et al., 1999).

In the Ultra rapid combination the full 48 hour orbit interval is combined. This implies that the statistics of this combination are based on the complete 48 hour interval. In principle the users of the IGU products will only need to use the interval from 3:00 to 15:00 UTC for the products delivered at 3:00 UTC. From the products delivered ate 15:00 UTC they will only need the interval from 15:00 to 3:00 UTC the next day. Because, large residuals, most likely found at the end of the prediction interval (e.g. from 15 to 24 hours), dominate the RMS the results from the IGU combination might be pessimistic. On the other hand for orbit predictions ACs tend to make similar errors for satellites with unexpected behavior, as we know from the predicted orbits. These have a significant effect on the "true" accuracy of the orbits and only show up when compared to either the IGS Final or Rapid orbits. Taking this into account it is unclear whether the (weighted) RMS statistics of the IGS Ultra rapid combination is optimistic or pessimistic.

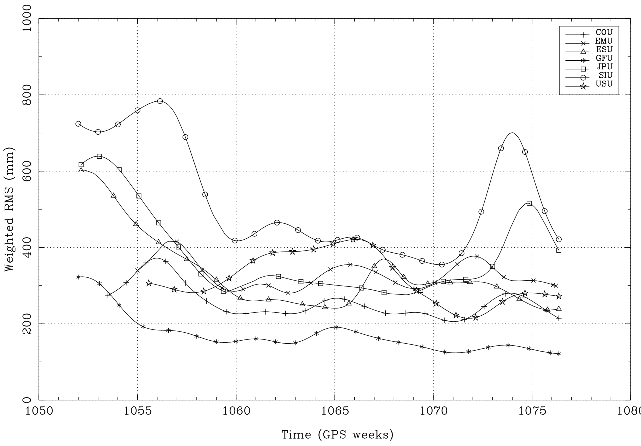

Fig. 1. Quality of AC Ultra rapid orbit solutions compared to combined IGS Ultra rapid orbit. The weighted RMS values from the Ultra rapid orbit combination were smoothed using a 7 day sliding window.

Figure 1 shows the weighted RMS values of the IGU orbit combination for the individual ACs contributing to the IGU product. For clarity the weighted RMS values were smoothed using a 7 day sliding window. We observe that the agreement of the AC Ultra rapid solutions is at the 10 to 40 cm level. It is striking to see that the GFU products (from the GeoForschungsZentrum, Germany) consistently show the best agreement with the combined IGU products. The agreement between the GFU and IGU orbits is close to the 10 cm level.

To clarify if the 10 to 40 cm level of agreement as seen in the IGU combinations is optimistic of pessimistic we take a look at the results of the routinely performed orbit comparisons. In these orbit comparisons the predicted orbits from the individual ACs are compared to the IGS Rapid orbit as soon as it becomes available. In this comparison the IGP products are also included and since March 2000 also the IGU product is included. The IGR orbit covers only 24 hours whereas the IGU orbits cover 48 hours which shift by 12 hours from product to product. This means that there are four IGU orbits which overlap with any particular rapid orbit. From these four IGU orbits we include only the IGU product from

Fig. 2. Quality of real-time IGS orbit products (IGP and IGU) compared to the combined IGS Rapid orbit product. The weighted RMS values from the Rapid orbit comparison were smoothed using a 7 day sliding window.

which the 24 to 48 hour interval overlaps with the IGR product. From this particular IGU product the users would typically only need the interval from 27 to 39 hours (i.e., the 3 to 15 hour prediction interval). Hence, this comparison will give a pessimistic estimate of the quality of the IGU products.

Figure 2 shows the weighted RMS values of the IGP and IGU combined orbits compared to the IGR orbits stemming from the rapid orbit comparisons. Again the weighted RMS values were smoothed using a 7 day sliding window. We may draw two conclusions from this figure. First, the quality of the IGU products is already significantly better than the quality of the IGP products. This was expected because of the strongly reduced length of the orbit prediction interval. Secondly, we see that the IGU orbit quality is at a level of 30 to 40 cm. This is slightly worse than the 10 to 40 cm agreement observed in the ultra rapid combination but this was to be expected because some problems with predicted orbits do not show up in the combination and because this comparison gives a pessimistic estimated as it uses the full 24 hour prediction interval instead of only the required 12 hour interval. In any case, an orbit quality of 30 cm, available for real-time applications, is an excellent achievement!

In Table 1 we have summarized the statistics of the rapid orbit comparison for the available real-time orbits; broadcast (BRD), IGP, and IGU. These statistics include, besides the mean weighted RMS and its variation, the mean and variation of the estimated translation, rotation, and scale parameters. The orbit combinations and comparisons always include a 7 parameter similarity transformation to account for reference frame differences. From this table we may conclude that the IGU products are clearly superior to the other available real-time orbits (remember that these IGU statistics are pessimistic). Clearly the performance of the broadcast orbits (BRD) is much worse than the performance of both IGS products. Besides the WRMS also the translation parameters of the broadcast orbits show significant biases and variations (Springer et al., 2000). The mean and standard deviation of the transformation parameters of the IGS real-time products is amazingly good at the 1–2 cm level. This means that the IGS real-time products are very well aligned to the ITRF reference frame. For the translations and the scale the performance is quite similar for the IGU and IGP products. For the rotations the IGU products perform significantly better than the IGP products. This is caused by the reduced prediction interval which is also important for the Earth rotation parameters.

2.2 Processing of GPS data

To test the IGS Ultra rapid orbits for actual data processing we selected a small network consisting of three stations: Potsdam, Germany (POTS), Wettzell, Germany (WTZR), and Westerbork, the Netherlands (WSRT). The baselinelenghts between these stations range from 400 to 600 km. For our processing test we used two weeks of data, GPS week 1065 and 1066, and processed the data with all IGS orbit products: Final, Rapid, Prediction, and Ultra rapid. In the processing the coordinates of all three stations were constrained. For meteorological applications there is no need to estimate the station coordinates in the NRT process. Of course, even for pure meteorological applications, there is a need for monitoring the station coordinates but that is beyond the scope of this work. The estimated parameters contain the tropospheric zenith delays, where we estimated piece-wise constant values for each hour (24 parameters per station per day), and the ambiguity parameters. It was attempted to resolve the integer value of the double-difference ambiguities in all cases with a success ratio of 70–80%. An elevation cut-off angle of 10^0 was used with an elevation dependent weighting of the observations. This processing strategy is similar to the one used for the generation of the IGS solutions from the Center of Orbit Determination in Europe (CODE) (Rothacher et al., 1999). The processing was done with the Bernese GPS software package (Rothacher and Mervart, 1996).

The results obtained using the IGS Final orbits were taken as "ground truth" and all other results were compared to these. Because, meteorological applications are the driving force behind the generation of the IGS Ultra rapid products we focus here on the tropospheric zenith path delays (ZPD) estimates. The results of the zenith path delay comparisons are summarized in upper part of Table 2. We see that the results with the IGS Rapid orbits are almost indistinguishable from the Final results. The RMS difference is 1 mm which is well below the 3–4 mm RMS agreement achieved in the IGS troposphere combination (Gendt, 1998). This RMS difference may be considered to lay within the noise level of the estimates. The results with the predicted and ultra rapid products show significant RMS differences, IGP at the 30 mm level, and IGU at the 20 mm level. These results confirm that the IGU orbits are better than the IGP orbits, as we already concluded from the orbit comparisons.

However, for numerical weather predictions the accuracy requirement for the NRT ZPD estimates is about 6 mm, corresponding to approximately 1 mm precipitable water vapor

Table 1. Mean (μ) and standard deviation (σ) of the daily transformation parameters from the comparisons between the real-time orbit products and the IGS Rapid orbit products. Based on the interval from GPS week 1052 to GPS week 1076.

Sol		TX	TY (mm)	TZ	RX	RY (mas)	RZ	Scale (ppb)	WRMS (mm)
BRD	μ	6.1	3.1	309.8	-0.25	-0.18	3.46	0.89	2696.4
	σ	110.2	105.2	139.9	1.36	1.86	3.83	3.55	611.0
IGP	μ	1.6	0.6	-7.9	0.01	0.00	-0.42	-0.04	707.8
	σ	8.1	7.5	17.8	0.72	0.96	1.86	0.32	1096.6
IGU	μ	3.8	0.9	-1.0	0.04	-0.02	-0.37	-0.03	352.3
	σ	8.6	8.7	15.7	0.44	0.58	1.28	0.27	450.4

(PWV). Clearly neither real-time orbits delivers this accuracy. If we take a closer look at the results, see Fig. 3, we see that the RMS is dominated by a few "bad" days. On these days one to three satellite were predicted quite inaccurately in both the IGP and IGU products. This is one of the problems when using predicted (real-time) orbits. Several approaches have been studied in the literature over the recent years, test have been made with removing bad satellites, weighting bad satellites, and orbit relaxation for all or only the bad satellites (Kruse et al., 1999; Ge et al., 2000; Douša, 2000). One approach suggested is to allow orbit relaxation by estimating an along-track orbit parameter for all satellites. This should handle the problems with the bad satellites (Kruse et al., 1999). A similar, but more sophisticated, approach is to iteratively determine which satellites need orbit improvement/relaxation (Ge et al., 2000). In this iterative procedure the constraints on the orbit parameters is changed from iteration to iteration until the process converges.

We have tested the, relatively simple, approach of estimating one along-track parameters for each satellite using the IGP and IGU orbits and the result are given in the middle part of Table 2. As expected a clear improvement is seen for both the IGP and IGU orbits which now give an accuracy of approximately 10 mm RMS for the ZPD estimates. However, in these tests we noticed that for "good" days the results with the IGU orbits actually degraded. This indicates that the general quality of the IGU orbits is such that the estimation of an along-track parameter actually degrades the orbit quality and, therefore, also the quality of the other estimated parameters. Here the iterative orbit weighting approach would probably have given better results.

Secondly we tested the approach of removing bad satellites. Rather than removing bad satellites it is also possible to do an orbit relaxation for these satellites. This, however, will most likely give similar results. Based on previous experience it is relatively easy to define a "normal" residual RMS level. Bad satellites are then determined as satellites for which the residual RMS exceeds the normal level by a factor of 3 to 5. If more than one satellite exceeds the RMS threshold only the satellite with the highest RMS is removed and the process is repeated. This process is repeated until no bad satellites are detected. This means that 3 to 4 iteration might be needed on a "bad" day, but on average only one iteration will be needed. This process can be automated very easily. The results using the IGP and IGU orbits are again

Table 2. Results of zenith path delay estimates using different IGS orbit products. The zenith path delays obtained using the IGS Final orbits were used as "ground truth" to compare the other results with. All hourly ZPD estimates for the 14 day interval were included.

Product	ZPD RMS Difference (mm) POTS	WTZR	WSRT
IGR	1	1	1
IGP	35	31	29
IGU	22	19	21
Along-track par. all sats.			
IGP	10	10	10
IGU	8	9	8
Iterative rejection bad sats.			
IGP	11	11	11
IGU	7	7	7

given in Table 2, lower part. It is interesting to see that in this case the results with the IGP orbits have a slightly higher RMS compared to the orbit relaxation test (11 vs 10 mm). This indicates that the IGP orbit quality may actually be improved using this small network. For the IGU the bad satellite rejection gives slightly better results (7 vs 8 mm) as expected based on our observations from the orbit relaxation tests. The 7 mm RMS for the ZPD is close to the meteorological accuracy requirement. Here one must also consider the fact that the IGS Final results were taken as error free, which is of course not true. Also the IGS Final ZPD estimates have some noise which contributes to the 7 mm RMS observed for the IGU results.

3 Conclusions

New Ultra rapid IGS products are available for (near) real-time applications. These IGU products are delivered twice every day at 3:00 and 15:00 UTC with a 3 hour delay after the end of the included data interval. We have demonstrated that the quality of the IGU orbits is at the 30 cm level or better which is significantly better than the IGS Predicted products (IGP). This improvement is mainly accomplished because of the significantly reduced prediction interval. For the IGU products the average age of the prediction is 9 hours compared to 36 hours for the IGP products.

We have further demonstrated that with the current IGU products the tropospheric zenith path delays (ZPD) may be acquired with an accuracy at the 7 mm level, RMS, for a network with a diameter of 600 km. This corresponds to approximately an accuracy of 1 mm PWV. This accuracy should be sufficient for a meaningful inclusion of GPS based ZPD, or PWV, estimates in NRT numerical weather predictions.

It was shown that with the IGU orbits, like with the IGP orbits, it is necessary to detect and handle bad satellite predictions. We have shown that the detection of bad satellites is relatively easy and can be completely automated. To handle the bad satellites we have selected the approach of removing the bad satellites from the observations. A valid alternative may be the orbit relaxation approach which, however, will give similar results as the satellite removal approach. It is clear that the accuracy codes in the precise orbit files are not reliable for the predicted orbits. Furthermore, the downweighting of bad satellites will be useful only if it is implemented in a way which considers the size of the network because the effect of orbit errors depend on the baselinelenghts. To our knowledge this is currently not implemented in any GPS software package.

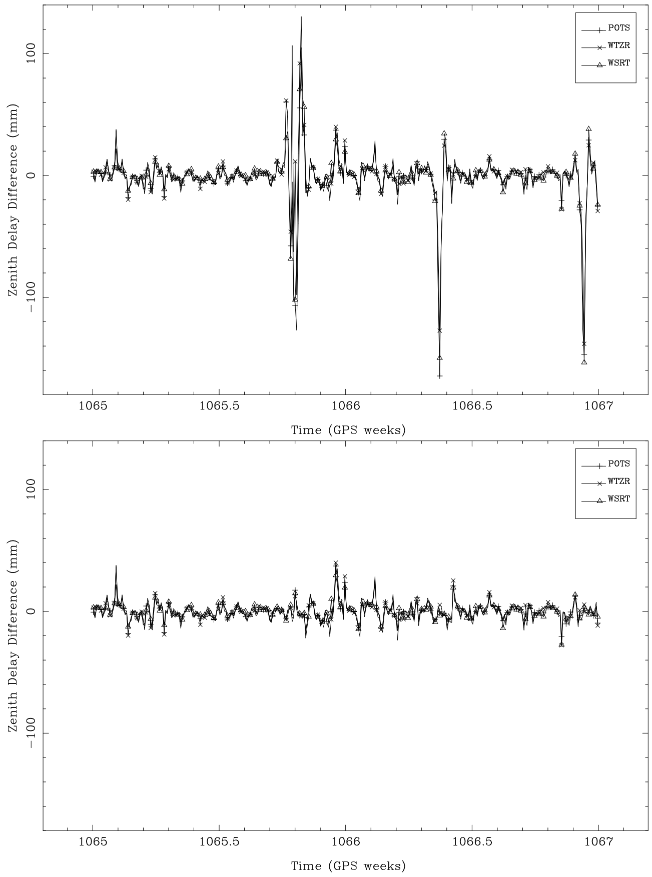

Fig. 3. Difference between the tropospheric zenith delays estimates from using the IGS Final orbit products and from using the IGS Ultra rapid orbit products. The Ultra rapid processing was done once using all satellites (upper) and once using the iterative satellite rejection method (lower).

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