Using IGS Products for Near Real-Time Comparison of UTC(k)'s

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Abstract—The time-transfer technique based on Precise Point Positioning (PPP) has proven to be a very effective technique allowing the comparison of atomic clocks with a precision of a hundred picoseconds, and with latency of two days. Using satellite orbit and clock information from the IGS real-time products, or from the NRCan Ultra Rapid products (EMU), it is now possible to compute very precise time transfer solutions in near-real-time mode (latency down to some minutes), using the PPP approach. This paper presents the PPP-based time transfer results obtained in near-real-time with the new version of the GNSS data processing software Atomium. These results are available continuously on the webpage *http://clock.oma.be*. From the statistics on the results, it is concluded that the near-real-time PPP allows to detect a clock jump larger than 1.5 ns after some minutes, or 0.8 ns after 90 minutes, and a frequency change larger than 2e-14 when looking at the last 24hr data, or larger than 2e-13 when looking at the last 2 hours.

I. INTRODUCTION

The time-transfer technique based on Precise Point Positioning (PPP) has proven to be a very effective technique allowing the comparison of atomic clocks with a precision at the level of a hundred picoseconds, and with latency of two days [1, 2]. PPP [3, 4] is based on a consistent modeling and analysis of GPS (and possibly GLONASS) dual-frequency code and carrier-phase measurements. It consists of using the ionosphere-free combinations of codes and carrier phases measured at one station to determine its position and its clock synchronization error at each observation epoch. This technique is widely recognized for its high resolution (1 pt/30 s) and high frequency stability, reaching 10^{-15} at an averaging time of one day, thanks to the very low noise level of the carrier phases (see for instance [5, 6]), enabling time transfer with a statistical uncertainty of 0.1 ns, when ignoring the uncertainty of the instrumental hardware delays calibration. The use of PPP for time and frequency transfer has been extensively studied and developed in the last years. Usually, IGS Rapid or Final products are used to remove the satellite clock errors from the measurements and to model the satellite positions. As these products are available after a minimum of 17 hours, we propose here to use either the NRCan Ultra Rapid products (EMU) generated hourly with a delay of 90 minutes after the last observation [7], or the IGS real-time products [8], to provide PPP solutions in a near-real-time mode (latency down to some minutes). This capability can be considered quite interesting for the National Metrology Institutes, being provided with an additional tool for comparisons of UTC(k)'s or for any time scale for which real-time monitoring is crucial.

In the first part of the paper, the satellite orbits and clock products that will be used are presented. The next section describes the stations used and our analysis scheme. In particular, the modifications introduced in the GNSS data processing software Atomium [2] are detailed. These modifications had to be considered in order to be able to work with satellite and clocks of worse quality than the classical IGS (Rapid or Final) products.

The two next sections of the paper present a quantification of the quality of the results obtained from the analysis conducted using the EMU or IGS real-time products for the satellite clocks and orbits, in order to determine at which level it can serve as near real-time monitoring of the UTC(k)'s or any other clock connected to a GNSS receiver. Finally, the web service developed at the Royal Observatory of Belgium (ORB) and providing continuously some time links computed with Atomium and near real-time products is presented.

II. SATELLITE ORBIT AND CLOCK PRODUCTS USED

Two sets of satellite clocks and orbits are presently available with a very short latency. The first set is the IGS real-time clocks and orbits which can be obtained from the streams delivered in real-time by the NTRIP Broadcaster *http://www.IGS-IP.Net* [8]. The second set of products is the EMU Ultra-Rapid products delivered by the NRCan Analysis Center of the IGS [7].

A. Real-time IGS products

An IGS Real-time Working group was established in 2001 with the goal to design and implement real-time IGS infrastructure and processes. The IGS presently manages a global real-time GNSS tracking network and generates combined real-time analysis products. These products are available with a latency of about 10 seconds, and the products are provided with a sampling rate of 5 seconds.

The different IGS real-time Analysis Centers (ACs) provide real-time clocks and orbits. All the real-time data are streamed in the RTCM format by different NTRIP casters. For this study, we choose the stream IGC01, which corresponds to the combined products as computed by the ESOC analysis center, who assumes the role of IGS Real Time Analysis Centre Coordinator. These products are provided as corrections to the broadcast orbits and clocks. In a first step we therefore generate corresponding files in the clock RINEX format (clk) for the clocks and in the sp3 format for the orbits, i.e. the classical IGS clock format, which can be used by Atomium. However, as the orbits streamed in the message IGC01 are the Ultra-Rapid combined orbits IGU, also available directly from the IGS website, we use these files rather than those reconstructed from the real-time streams.

In the present study, the PPP solutions are computed once per hour, so that we converted the real-time clocks into hourly files in the clk format.

The quality of the real-time satellite clocks is illustrated in Figure 1 (source [8]); the data used here correspond to the second half of 2012, so that they are not included in the Figure. However, from this picture one can expect a 2-sigma uncertainty of 200-400 ps on the real-time satellite clocks.

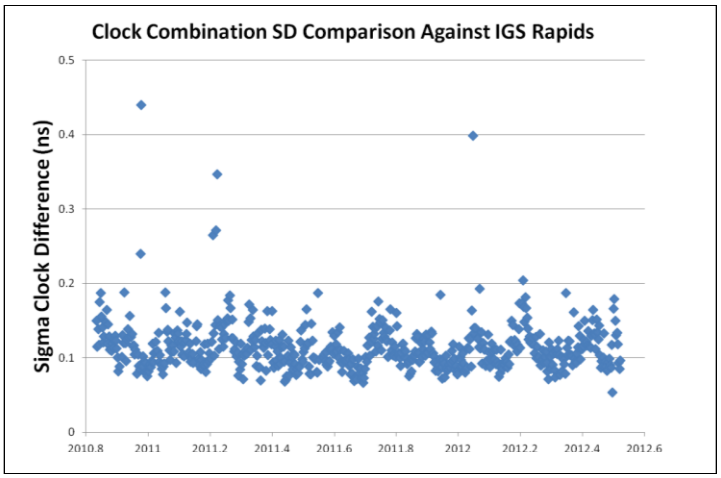

Figure 1. Accuracy of IGC01 clocks (source [8]).

B. Ultra-Rapid NRCan products

The second source of satellite orbit and clocks are the NRCan Ultra-Rapid products, named EMU, which are available with maximum 1.5 hour latency in the same format as the IGS products, i.e. SP3 and RINEX clock format. A new set of two files (sp3 and clk) is delivered each hour. Each clk file contains satellite clocks for the last 24 hr, and each sp3 file contains the satellite positions estimated in the last 24 hr, and estimated for the following 24hr. The 2-sigma uncertainties on these clock products is estimated to 170 ps [9]. The advantage of using the EMU products rather than the combined IGU products is that they are available more rapidly (90 minutes in place of 4 hours), and with a higher sampling rate (30 seconds in place of 900 seconds).

There is therefore a major difference between the IGS real-time products for which a given epoch is only computed and provided once, in real-time, while the EMU products are computed for a moving window of 24 hr. For each new hourly computation performed with the EMU, a new set of orbits and clocks is therefore used. When using the real-time products, the orbit and clock data corresponding to a given epoch will be used in the 24 hourly computations which will contain that epoch.

III. SETUP OF THE EXPERIMENT

Four time links are proposed here, two continental baselines: BRUX-PTBB (about 500 km) and USNO-AMC2 (about 2700 km), plus two intercontinental baselines: BRUX-AMC2 (7800 km) and PTBB-USNO (6500 km). They are illustrated in Figure 2. Note that we used the names of the IGS stations so that BRUX is for the time laboratory ORB (Brussels, Belgium), PTBB for the PTB (Braunschweig, Germany), USN3 for USNO (Washington, DC). AMC2, located in Colorado Springs, is not an time laboratory participating to TAI but its clock is the USNO Alternate Master Clock #1, the back-up realization of UTC(USNO). The four stations used are driven by an active hydrogen maser. The data collected during five weeks were analyzed, from September 27 to October 30. The solutions have been computed each hour using a data batch of 24 hr obtained from a concatenation of hourly RINEX files.

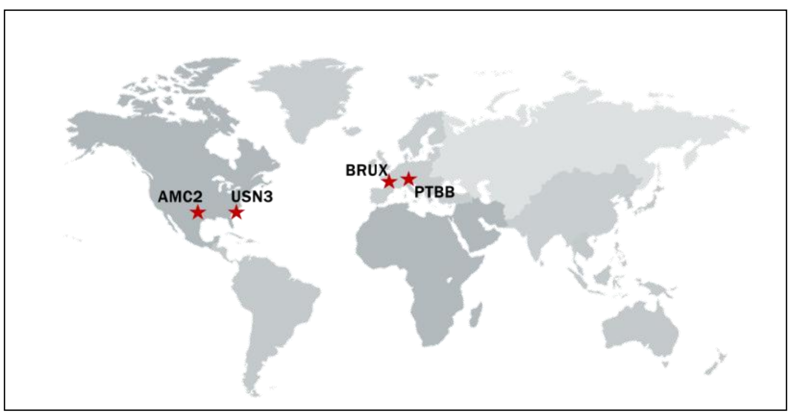

Figure 2. Distribution of stations used in the present study.

All the PPP results presented in this paper have been obtained using the PPP software Atomium, developed at the Royal Observatory of Belgium [2]. Only GPS data are used in this study, as the addition of GLONASS observations does not significantly improve the PPP-based time transfer solutions as shown in [11]. Atomium is based on a least square analysis over a given data batch, providing one station position for the data batch, one clock solution at each observation epoch and tropospheric zenithal delays with a chosen sampling rate. In the present case, the troposphere was determined as one estimation each 20 min, with a relative constraint of 1.5 mm between two successive values. A linear interpolation of the tropospheric zenithal delay is used between the epochs where a value is estimated.

Some preliminary results of near real-time monitoring of atomic clocks using Atomium and real-time IGS products have been presented in [10]. These results contained an important number of outliers, which is not acceptable for a real-time monitoring. For this reason a new cleaning procedure has been implemented in Atomium. In the previous versions, there was an initial cleaning based on the Melbourne-Wubbena combination of code and carrier-phase data on both frequencies; this was applied on the raw data in order to detect outliers and cycle slips. A second cleaning was operated for the rejection of smaller outliers based on the residuals after a first inversion. However, due to some bad satellite clock products in the real-time data, the first inversion was already contaminated and all the residuals were affected. In order to overcome that problem an additional cleaning was introduced after correcting the code measurements (ionosphere-free combination P3) for the satellite distance, the satellite clock, and the dry atmosphere, just before the first inversion. This allows removing new outliers due to problems in the real-time (or EMU) satellite orbits and clocks. It must be noted that the IGS real-time products have no accuracy codes and no information concerning the quality of the individual values, so that a software-based cleaning is really necessary to reject observations of satellites with erroneous clock products. Furthermore, as real-time products have epochs without any satellite clock (mainly due to short interruptions of the streaming), it was decided to keep the same ambiguities rather than to determine new ones when there is no satellite clock for one epoch; this avoids the presence of frequent jumps in the solutions.

In order to validate the new version of Atomium, we present in Figure 3 for the four stations the differences between the PPP clock solution computed with Atomium and the IGS Rapid combined solution. Figure 3 confirms the announced precision of PPP-based time transfer: the standard deviations of these differences is between 28 and 91 ps. We observe important differences between the four stations; these differences are mainly due to day boundary discontinuities. This can be explained by the noise and multipath of the pseudoranges in the different stations. For stations with high code multipath, any difference in the code rejection will induce a difference in the offset of the daily solution, while for a station with a very small code multipath (only white code noise), if not exactly the same code data are used in two parallel computations, there will be no significant offset between the two solutions. This is the case for AMC2 where the maximum difference between the Atomium PPP solution and the IGS combined solution is 99 ps and the standard deviation of the differences over 5 weeks is only 28 ps.

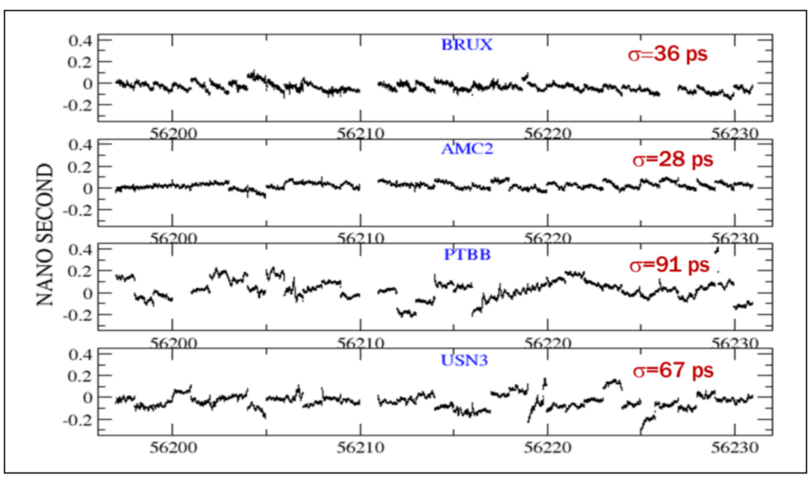

Figure 3. Differences between the PPP clock solution computed with Atomium and the IGS Rapid combined solution.

IV. COMPUTATIONS WITH IGC01 CLOCKS AND IGU ORBITS

Figure 4 presents the PPP clock solutions obtained using Atomium and the IGS real-time products for one day and for the 4 stations described here above. We observe the same pattern for all of the four solutions. This pattern corresponds to the reference time scale of the IGC01 clock products, which is clearly not constant. But as we are interested by clock comparisons, we will only concentrate on the differences between two clock solutions, which form the continental and inter-continental baselines proposed in the previous section. These are drawn in Figure 5 which presents the comparison and the differences between the time transfer solutions obtained with Atomium using either the IGS real-time products (stream IGC01) or the IGS Rapid products. All the solutions computed hourly for a 24hr data batch are included in the comparison. We directly see that outliers are no longer present. In order to quantify the quality of the solution obtained with the real-time products, we also present in Figure 6. the histograms of the differences.

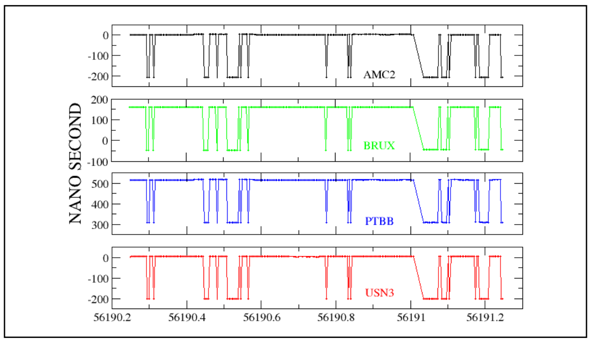

Figure 4. PPP clock solutions obtained using Atomium and the IGS real-time products for one 24hr data batch.

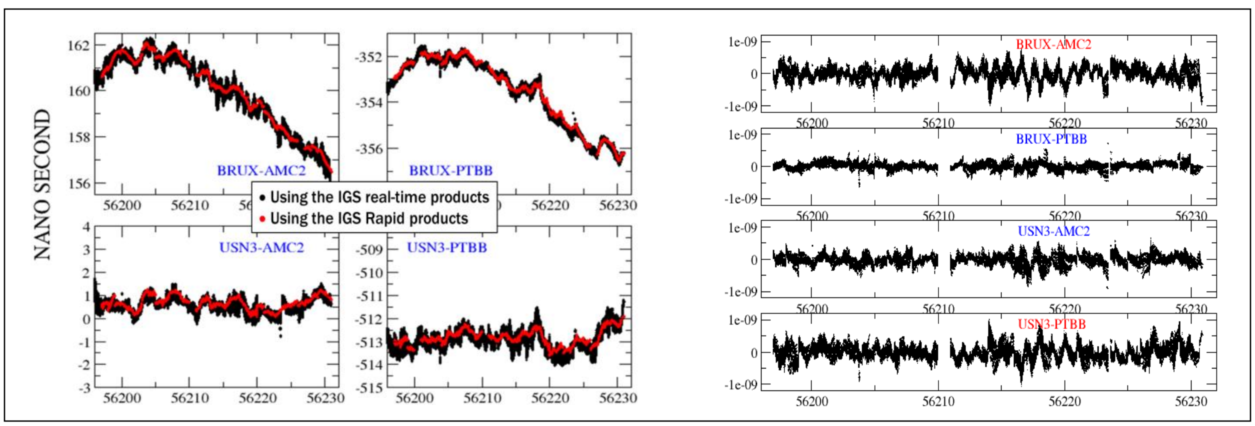

Figure 5. Comparison (left) and differences (right) between the time transfer solutions obtained with Atomium using either the IGS real-time products (stream IGC01) or the IGS Rapid products.

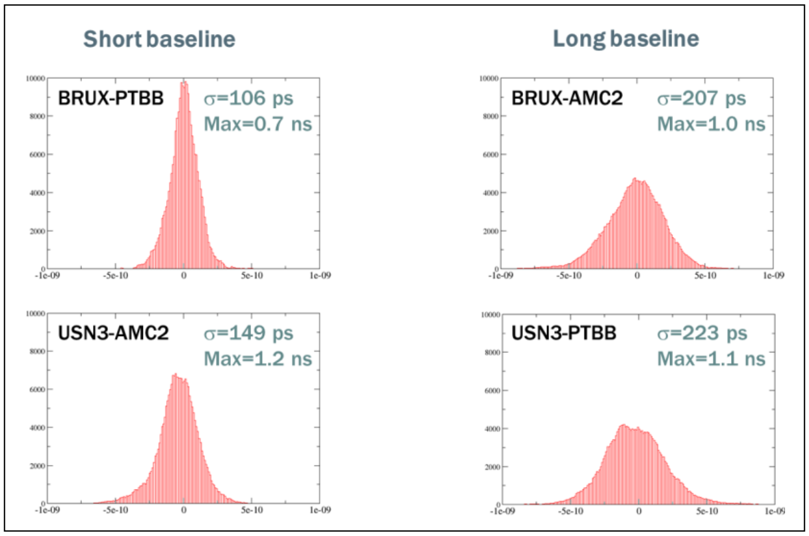

Figure 6. Histograms of the differences between the time transfer solutions obtained with Atomium using either the IGS real-time products (stream IGC01) or the IGS Rapid products.

Two main points should be noticed from this picture. Firstly it can be seen that the distribution differences is clearly dependent on the baseline length. This can be easily explained by the spatial correlation of orbital (positions + clocks) errors: these errors have a similar impact on the PPP clock solutions for nearby stations, and hence cancel out when making the difference of the solutions for time transfer. While for remote stations, the impact on the clock solution is different as the satellite visibility is different and this impact does not cancel out when making the difference between the two PPP solutions. It is therefore recommended to use short baselines for making real-time monitoring of the time-scale using real-time products. A second observation from Figure 6 is that the maximal difference between the solutions obtained with IGS real-time or Rapid products is 1.2 ns, which means that the real-time products are able to allow the detection of a clock jump at the level just above 1 ns. In order to determine which level of frequency change can be detected by the near real-time monitoring based on IGS real-time products, we plotted in Figure 7 the frequency differences over 24 hr and over 2 hr between the PPP solution computed with the IGS real-time products and the IGS Rapid combined solution. These frequency differences are computed as the linear regression coefficient over the 24hr solution differences (real-time – Rapid) in the first case, and over each 2hr window starting at an integer hour of the same differences in the second case. We can observe that for a clock frequency monitoring, looking at a 24hr solution allows to detect any frequency change larger than 1.8e-14 and when using only the last 2 hours for the monitoring, only frequency changes larger than 1.8e-13 can be detected. For smaller frequency changes observed in the solution, no distinction can be made between a clock frequency change and an artifact due to the satellite orbit/clock errors.

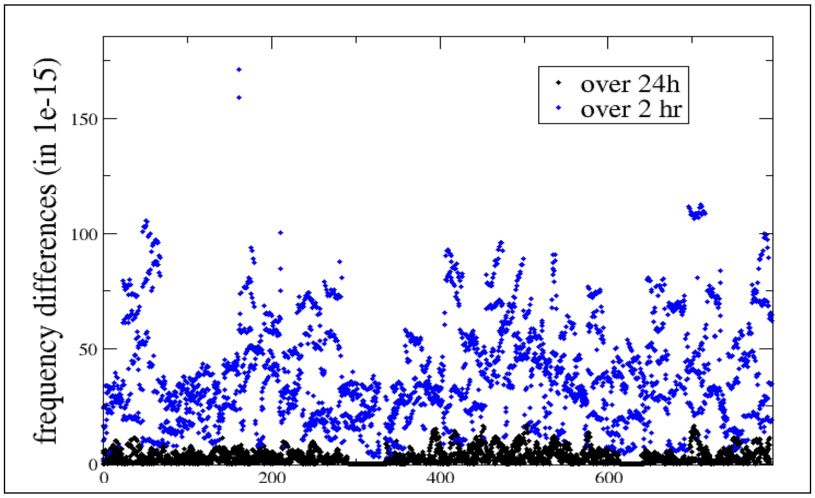

Figure 7. Frequency differences between the PPP solution computed with the IGS real-time products and the IGS Rapid combined solution.

V. COMPUTATIONS WITH EMU SATELLITE CLOCKS AND ORBITS

Figure 8 presents the PPP clock solutions obtained using Atomium and the EMU products for 24 successive data batches of 24hr separated by one hour, and for the stations BRUX and AMC2. We can observe here that the reference changes from one 24hr clock set to the next one, but contrarily to what we saw for the real-time products, the reference here inside a 24hr data batch is continuous. As the reference is changing it is also necessary to look at the time transfer solutions between two stations to get a continuous solution able to provide monitoring in quasi-real-time. For this reason, Figure 9 presents the differences between the time transfer solutions obtained with Atomium using either the EMU products or the IGS Rapid products, while the histograms of the differences are plotted in Figure 10. As for the real-time products, all the solutions computed hourly for a 24hr data batch are included in the comparison. We also present in Figure 11 the frequency differences over 24 hr and over 2hr between the PPP solution computed with the EMU products and the IGS Rapid combined solution.

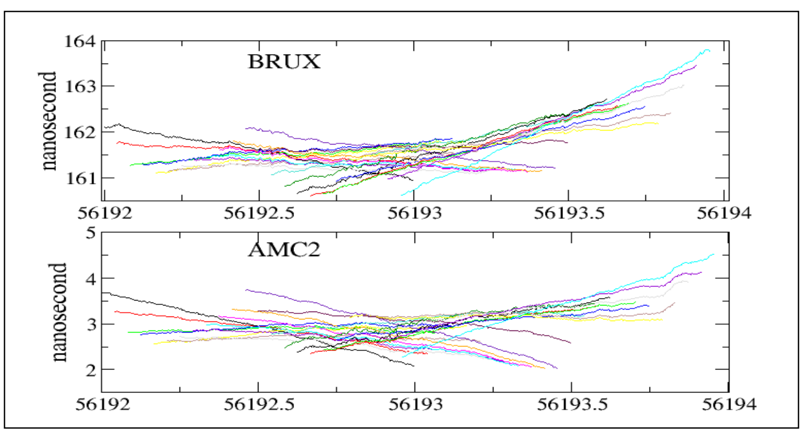

Figure 8. PPP clock solutions obtained using Atomium and the EMU products for 24 successive data batches of 24hr separated by one hour.

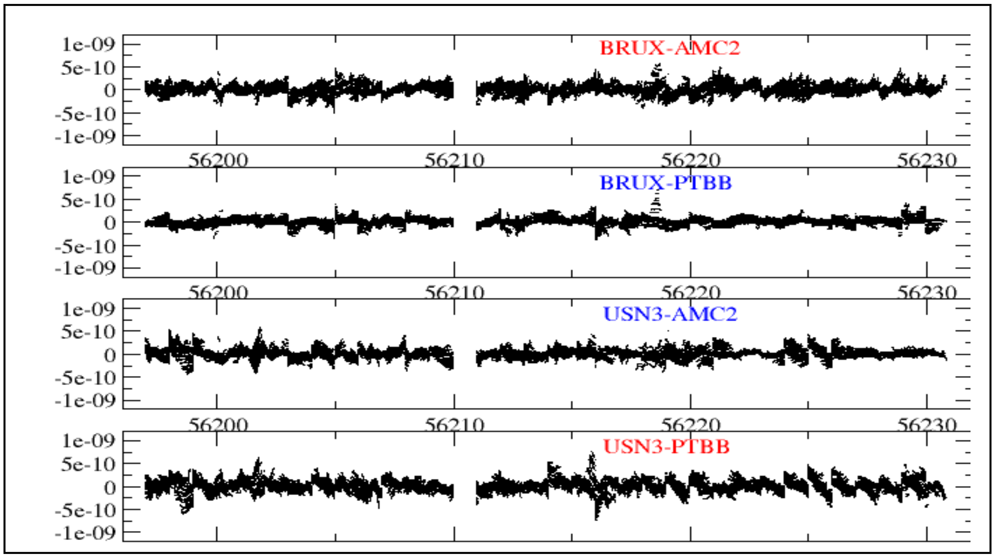

Figure 9. Differences between the time transfer solutions obtained with Atomium using either the EMU products or the IGS Rapid products.

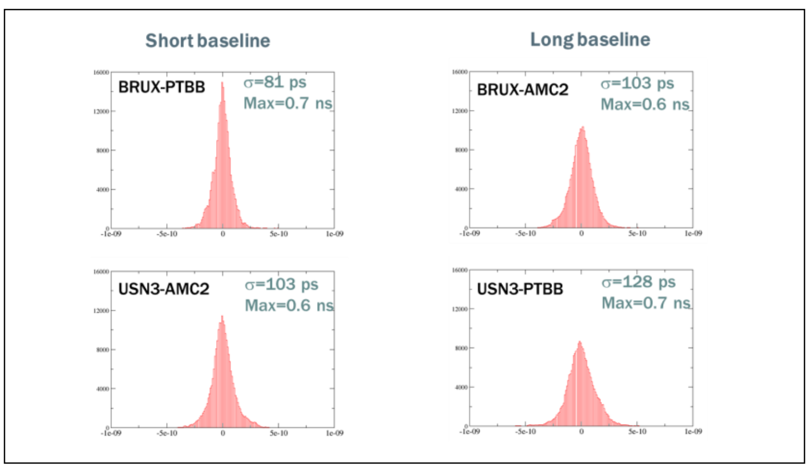

Figure 10. Histograms of the differences between the time transfer solutions obtained with Atomium using either the EMU products or the IGS Rapid products.

Comparing the results presented in Figure 10 and Figure 6, it appears that the EMU products provide a solution of better quality than the IGS real-time products. The standard deviation is less sensitive to the distance of the link, and is lower than the 150 ps for the four links investigated. The maximum observed difference between the time transfer solutions obtained with Atomium using either the EMU products or the IGS Rapid products is 0.7 ns in this case, and 1.2 ns using the IGS real-time products.

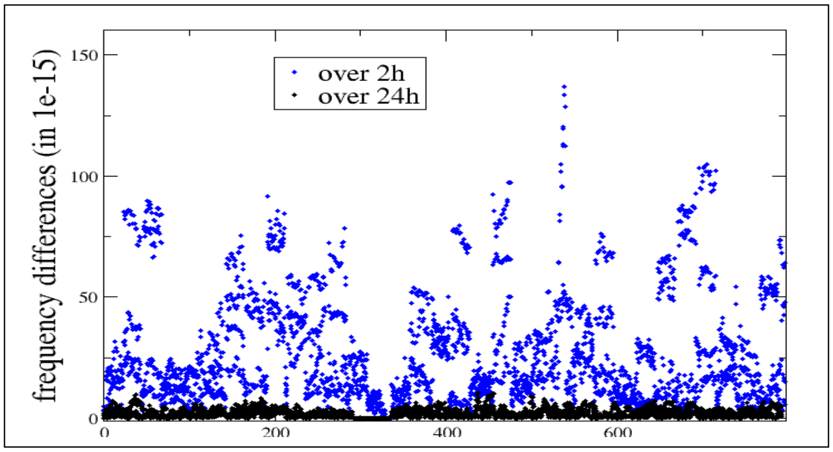

Figure 11. Frequency differences between the PPP solution computed with the EMU products and the IGS Rapid combined solution.

Concerning the frequency differences, we can observe that with the EMU products, looking at a 24hr solution allows the detection of any frequency change larger than 1.2e-14, and when using only the last 2 hours for the monitoring, only frequency changes larger than 1.5e-13 can be detected. There is therefore an advantage in using the EMU products when they are available, i.e. with a latency of 90 minutes maximum. In order to summarize these results, we present in Table 1 the standard deviation and maximum difference for each of the cases we have presented and in Table 2 the maximum observed frequency differences. We also added for comparison and as reference the corresponding values for the links computed with the IGS Rapid products. Our EMU results are in good agreement with a similar experiment with the EMU products, but using the NRCan PPP software [9].

Table 1. Statistics over the differences w.r.t IGR solutions.

	Standard Deviation			Max Difference		
	EMU	IGS-RT	RAP	EMU	IGS-RT	RAP
USN3-AMC2	103 ps	150 ps	72 ps	0.5 ns	1.2 ns	0.4 ns
BRUX-PTBB	81 ps	106 ps	101 ps	0.7 ns	0.7 ns	0.5 ns
USN3-PTBB	128 ps	223 ps	106 ps	0.7 ns	1.1 ns	0.4 ns
BRUX-AMC2	103 ps	207 ps	46 ps	0.6 ns	1.0 ns	0.2 ns

Table 2. Maximum frequency differences w.r.t. IGR solutions.

Max frequency diff. 24hr			Max frequency diff. 2hr		
EMU	IGS-RT	RAP	EMU	IGS-RT	RAP
1.1e-14	1.7e-14	4e-15	1.4e-13	1.7e-13	7e-14

VI. ORB WEB SERVICE

An operational computation of near real-time clock solutions is running at the ORB, based on Precise Point Positioning (PPP) with the new version of the software tool Atomium presented here. Only data from the GPS constellation are used. The solutions are computed each hour (at minute 12) using a 24hr data batch built from the hourly RINEX files and the IGS real-time products. The results are then stored in a data bank and a web page presents pictures based on the last update of the data bank. The computation done with real-time IGS products uses 24hr data ending at the beginning of the current hour. After 1 hour 8 minutes (at minute 20), the solutions in the database (and hence in the pictures) are replaced by new solutions computed with the EMU products produced by the NRCan IGS analysis center. This run indeed uses 24hr data ending 80 min before the epoch of computation. The day after, when the IGS Rapid products are available, i.e. at 17hr UTC, the solutions in the database are replaced by those computed with the IGS Rapid products, and 2 weeks later they are replaced by the solutions computed with the IGS Final products. As illustrated in Figure 12, the solutions presented on the website are therefore those obtained using

- Final IGS orbits and clocks for dates prior to two weeks before the present week (not present on the default figures);
- Rapid IGS orbits and clocks for the two previous weeks and the up to two days before present;
- EMU products for the previous day and the present day up to the end of current hour –2 or –1;
- IGS real-time clocks and IGU orbits for current hour –2 (up to minute 20) and current hour –1.

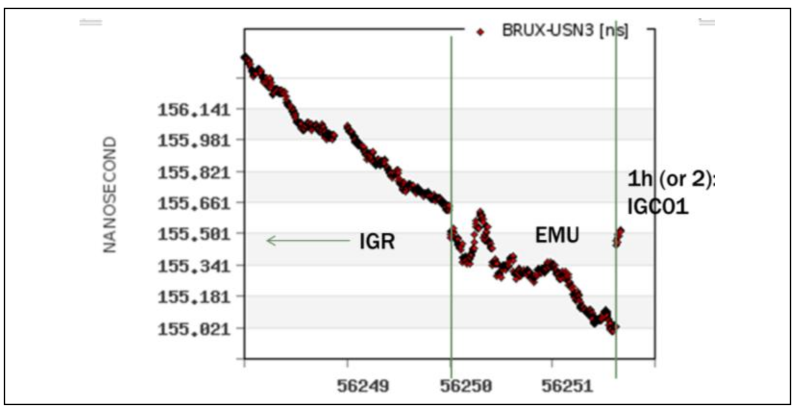

Figure 12. Example of clock comparison proposed on the ORB web page.

The web page *http://clock.oma.be* may be visited on request. By default the solutions are presented for the previous three days plus the present day up to the beginning of the current hour. The plots are updated after each new computation (minutes 12 and 20). A different period of time can also be visualized for a comparison between two stations of the proposed list using the request frame appearing in the bottom of the page. Laboratories willing to be included in the computation may contact the ORB. Only hourly (resp. daily) RINEX files are required for hourly (resp. daily) updates of the solution.

VII. CONCLUSION

Using Ultra-Rapid or real-time products for satellite orbits and clocks, it is now possible to compute near real-time PPP solutions and hence provide a near real-time clock monitoring. This paper presented an analysis of the results obtained from the PPP analysis conducted using the EMU or IGS real-time products for the satellite clocks and orbits, in order to determine the level at which these PPP solutions can serve as near real-time monitoring of the UTC(k)'s or any other clock connected to a GNSS receiver.

A new version of Atomium was used for this study; it includes a new data cleaning method able to remove from the data the satellites having bad orbits or clocks, so that Atomium presently does no longer include any outlier in the clock solutions computed with the IGS real-time products or any clock/orbit products of lower quality than the IGS combined Final or Rapid products.

The first set of products investigated was the IGS real-time products available with a latency of about 10 seconds. It was observed that the standard deviations of the differences between the time transfer solutions obtained using either IGS real-time products or IGS Rapid products are significantly correlated with the distance between the stations. From about 100 ps for a 500 km baseline, it grows up to more than 200 ps for the Europe-America link PTB-USNO. This results from orbital (positions + clocks) errors which have a similar impact on the PPP clock solutions for nearby stations, and hence cancel out when making the difference of the solutions for time transfer, which is no longer the case for more remote stations. Detection of clock problems using IGS real-time products is therefore preferable using short baselines. However, the results presented in this paper show that near real-time PPP based on these real-time products allows the detection in a few minutes of any clock jump larger than 1.5 ns, and a frequency change larger than 2e-14 when looking at the last 24hr data, or larger than 2e-13 when looking at the last 2 hours.

The second set of products is the EMU, provided by the IGS analysis center NRCan with a 90 minutes latency. It was observed that these products provide a solution of better quality than the IGS real-time products. The standard deviation is less sensitive to the distance of the link, and remained lower than the 150 ps for the four links investigated. It was also shown that using the EMU products it is possible to detect any clock jump larger than 0.8 ns a bit more than 90 minutes after the event, and a frequency change larger than 1.2e-14 when looking at the last 24hr data, or larger than 1.6e-13 when looking at the last 2 hours available, i.e. ending 90 minutes before the current epoch.

The near real-time clock comparison for a given set of time links is presently running at the ORB; the results are stored in a database and a web page displays the associated plots, updated at each new computation. The clock comparisons are provided with a latency of 12 minutes after the end of the hour using IGS real-time products. After 80 minutes, the solutions in the database (and hence in the pictures) are replaced by new solutions computed with the EMU products produced by the NRCan IGS analysis center. One day later, the solutions in the database are replaced by those computed with the IGS Rapid products, and 2 weeks later they are replaced by the solutions computed with the Final IGS orbits.

From the statistics we have here from the results, it is concluded that the solutions proposed on the webpage allow the detection of a clock jump larger than 1.5 ns after 12 minutes, or 0.8 ns after 80 minutes, and a frequency change larger than 2e-14 when looking at the last 24hr data, or larger than 2e-13 when looking at the last 2 hours.

ACKNOWLEDGMENT

The authors thank the IGS community, and especially the IGS Real-Time Working Group members for the real-time clocks and orbits and the NRCan analysis centers for the hourly EMU products which allow us to process these near real-time clock comparisons.

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