New IGS Station and Satellite Clock Combination

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Following the principles set forth in the Position Paper #3 at the 1998 Darmstadt Analysis Center (AC) Workshop on the new International GPS Service (IGS) International Terrestrial Reference Frame (ITRF) realization and discussions at the 1999 La Jolla AC workshop, a new clock combination program was developed. The program allows for the input of both SP3 and the new clock (RINEX) format (ftp://igscb.jpl.nasa.gov//igscb/data/format/rinex_clock.txt). The main motivation for this new development is the realization of the goals of the IGS/BIPM timing project. Besides this there is a genuine interest in station clocks and a need for a higher sampling rate of the IGS clocks (currently limited to 15 min due to the SP3 format). The inclusion of station clocks should also allow for a better alignment of the individual AC solutions and should enable the realization of a stable GPS time-scale.

For each input AC clock solution the new clock combination solves and corrects for reference clock errors/instabilities as well as satellite/station biases, geocenter and station/satellite orbit errors. External station clock calibrations and/or constraints, such as those resulting from the IGS/BIPM timing pilot project, can be introduced via a subset of the fiducial timing station set, to facilitate a precise and consistent IGS UTC realization for both station and satellite combined clock solutions. Furthermore, the new clock combination process enforces strict conformity and consistency with the current and future IGS standards.

The new clock combination maintains orbit/clock consistency at millimeter level, which is comparable to the best AC orbit/clock solutions. This is demonstrated by static GIPSY precise point positioning tests using GPS week 0995 data for stations in both Northern and Southern Hemispheres and similar tests with the Bernese software using more recent data from GPS week 1081. © 2001 John Wiley & Sons, Inc.

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1. INTRODUCTION

In order to take full advantage of the IGS clock solutions and to conform to international conventions (UTC), it is essential that both satellite and station Analysis Center clock solutions be combined in a consistent manner, while also maintaining consistency with the IGS orbit and station combinations. Though the satellite combined clock solutions have been an integral part of the IGS orbit/clock products almost from the beginning, there is no official IGS station clock product yet. The need for such station-clock-combined products was recognized and strongly endorsed by the 1998 Darmstadt AC Workshop (Dow et al., 1998). Such new IGS station clock products are not only essential for the IGS/BIPM Timing Pilot Project (Ray, 1999), but also for a number of applications such as the emerging LEO projects. Besides, time is perhaps the most fundamental quantity and thus should receive due attention by IGS to foster new, yet unforeseen applications of IGS data and products.

During the 1998 AC workshop ACs were encouraged to start submitting satellite/station clock solutions in the new format. By the end of 1999 the IGS ACs were routinely submitting satellite/station clock solutions in the new clock format. Early in 2000 rapid clock solutions were also provided by nearly all the ACs. The development of the new station/satellite clock combination was initiated at the Astronomical Institute of University of Berne at the beginning of 1999. Initial results were presented and discussed at the 1999 AC workshop in La Jolla. The program was completed by the end of 1999 and put into routine, but experimental, use in the IGS Final orbit/clock combinations. The description and results of this new clock combination program are given in the following two sections of the paper, followed by a brief summary and outlook.

2. NEW IGS CLOCK STATION/SATELLITE COMBINATION

To provide flexibility and to minimize disruption of the current IGS orbit/clock combinations, it was decided to develop a stand-alone clock combination program. The program is making use of the existing IGS clock combination routines, including the minimum norm robust estimation employed in both IGS orbit (Beutler et al., 1995) and the satellite clock combinations (Kouba et al., 1995).

The first step of the clock combination is the alignment of the individual AC solutions to the IGS reference frame. As outlined and recommended in the Position Paper #3 at the 1998 AC workshop (Kouba et al., 1998), utmost care has been exercised to enforce and maintain consistency of all IGS combined products. The station/satellite clock combinations are made consistent with the current IGS orbit/ERP and the SINEX Reference Frame combination products (Ferland, 1999). Specifically, the following compatibility corrections are applied to AC clock solutions prior to the clock combination to maintain orbit/clock as well as SINEX/clock consistency:

$$\Delta clk_{STA} = ((X_{AC}-X_{IGS}-DX) \cdot X_{AC})/R_{STA}/c,$$

$$\Delta clk_{SAT} = ((Y_{AC}-Y_{IGS}-DX) \cdot Y_{AC})/R_{SAT}/c,$$

where Δclk_{STA} and Δclk_{SAT} are the consistency corrections applied to AC station and satellite clock solutions, respectively; DX is the origin ("geocenter") offset of the AC SINEX station solutions (X_{AC}) with respect to the IGS SINEX station solutions (X_{IGS}). The dot product is divided by the station radius vector (R_{STA}) and the velocity of light c. Analogously for Δclk_{SAT}, Y_{AC}, Y_{IGS} are the AC and IGS satellite solutions and R_{SAT} is the satellite radius vector. Note, however, that the station (SINEX) geocenter offset DX and not the one derived from the corresponding AC satellite orbit solutions Y_{AC} is used for the satellite clock corrections Δclk_{SAT} as well.

In the second step the individual AC solutions are aligned to a common reference time frame. Although this is not really necessary, the alignment of the combined clock product is done as the last step; it does speed up the convergence of the clock combination. The third step, the actual combination, uses a robust iterative outlier detection and rejection scheme, detects and corrects reference clock jumps in the individual AC solutions, and accounts for satellite, station, and epoch biases for each of the individual AC clock solutions. Since AC clock solutions, in general, refer to different reference clocks, significant inconsistency errors can be introduced, in particular in remote areas with solution gaps, or when satellites and/or stations are missing from AC clock solutions. This is demonstrated in Figure 1, where AC reference clock differences with respect to an average reference clock are shown. Here, the AC reference clock errors for some ACs can exceed 1000 picosec (1 nanosec). The AC clock solutions using highly stable Hydrogen Maser reference station clocks and phase observations can be easily identified in Figure 1. The new clock combination accounts for these AC reference clock differences prior to the combination, thus mitigating the effect of missing epochs, satellite and/or stations.

An additional source of inconsistencies, in particular for missing epochs, satellite and station clocks, are the AC's specific satellite/station instrumental and/or software biases. That is why an iterative station/satellite bias estimation (with respect to a mean) has also been implemented in the clock combination program. For backward compatibility, both the SP3 as well as the new RINEX clock formats are allowed. Calibration data in RINEX clock format, which could facilitate an UTC realization, are not included yet, though implementation will be relatively easy. The last step in the combination is the alignment of the combined clocks to a chosen reference timescale. Currently broadcast clocks are used for this purpose but this can easily be changed.

The new clock combination process enforces strict conformity and consistency with the current and future IGS standards, such as: NO DOMES = NO station clock

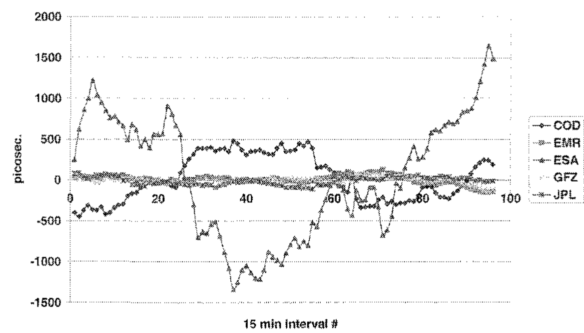

FIGURE 1. AC reference clock corrections, day 6, GPS wk 0995.

solutions, the new IGS ITRF realization (through the new IGS combined SINEX station product), and the IGS.SNX template. Both the IGS SINEX template and the most recent IGS Reference Frame solution are used in the clock combination. Currently, in its experimental usage for both the IGS Final and Rapid combination, a sampling rate of 5 min is used which should be sufficient for precise centimeter precision level satellite clock interpolation, now that SA has been switched off (e.g., Zumberge & Gendt, 2000). However, the combination software is capable of using sampling rates of up to 30-s sampling.

3. INITIAL TEST RESULTS

In April 1999 only GFZ and EMR submitted station/satellite solutions in the new clock format, the USNO rapid clock solutions, also in the new clock format, were kindly made available for the GPS week 0995 and were used for testing. All the corresponding orbit and station (SINEX) solutions, along with the IGS Final orbits and a preliminary IGS SINEX combination (Ferland, 1999) were also utilized.

For wk 0995, the existing SP3 clock files of the five ACs (COD, EMR, ESA, GFZ and JPL) that provide satellite clock solutions in their SP3 orbit files were also combined using the new clock combination system. The official IGS orbits, augmented with the newly combined satellite clock solutions, were then subjected to the standard evaluation by precise GIPSY navigation at the IGS test stations WILL, BRUS, and USUD, as done every week within the IGS combination process. The IGS orbits with the new combined satellite clocks performed equally well or marginally better than the standard IGS orbit/clocks. The above three stations augmented by the remote Southern Hemisphere station AUCK were also used in static precise point positioning (ppp) with the GIPSY software (Zumberge et al., 1997) in order to validate the orbit/clock consistency of the new clock combination software. For comparisons, all AC orbit/clock solutions (with the exception of relatively noisy ESA clock solutions) were also used in the ppp for wk 0995. The results are summarized in Figure 2 below, which shows the GIPSY ppp repeatability (around the mean) of ACs (orbits/clocks), IGS (current Final orbit/clock combinations), and IGSN—the IGS orbits augmented with the new clock combination of all five ACs. As one can see, IGSN repeatability is only marginally better than IGS, and worse than the best ACs (GFZ, JPL). However, when excluding the AC clock solutions that at that time were inconsistent with the corresponding AC orbits, or were not based on phase observations (COD and ESA) which is the case of IGS2 in Figure 2, the IGS orbits and the new clocks

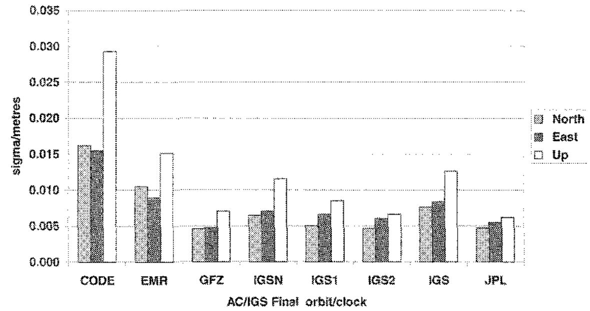

FIGURE 2. Repeatability of static GIPSY ppp (AUCK, BRUS, USUD and WILL; GPS wk 995) with AC/IGS orbits corrected for daily origin offsets; the IGS orbits plus the new clock combinations: IGSN—all 5 ACs; IGS1—ESA excluded; IGS2—ESA, COD excluded.

perform equally well as the best AC orbit/clock solutions. The IGS2 repeatability is a significant improvement over the centimeter level repeatability of the current IGS orbit/clock combinations, reported by Springer et al. (1998) and again confirmed here. The IGS2 repeatability is remarkable, as even when seven AC orbit and only three AC clock solutions are combined, the orbit/clock consistency is still maintained at a few millimeter level as seen in Figure 2. Needless to say that such (IGS) combined orbit/clocks should be more complete (more epochs) and more reliable than even the best AC orbit/clock solutions. For completeness the IGS clock combination without the ESA clock solutions (that were rather noisy for wk 995), labeled IGS1, is also shown in Figure 2.

Note that all the ppp results in Figure 2 were corrected for daily AC/IGS orbit origin (geocenter) offsets to account for apparent geocenter variations that can reach up to a centimeter for IGS and can even exceed 10 cm for some ACs. The apparent geocenter offsets were estimated, for each AC and IGS daily orbits, as an average of the corresponding ppp differences with respect to ITRF96 for all the four test stations. The apparent geocenter variation is a consequence of the AC minimum (rotational) constraint solutions that have been introduced during 1998, as recommended by the 1998 AC workshop. The origin (i.e., implied geocenter) of IGS orbits could be verified and made consistent with IGS SINEX station solutions by using static ppp's at a small number of well distributed stations. This is the approach which was used here and which has already been employed by the JPL ppp for a number of years (Zumberge et al., 1997).

To demonstrate the magnitude and significance of the problem, Figure 3 shows the RMS of the static ppp

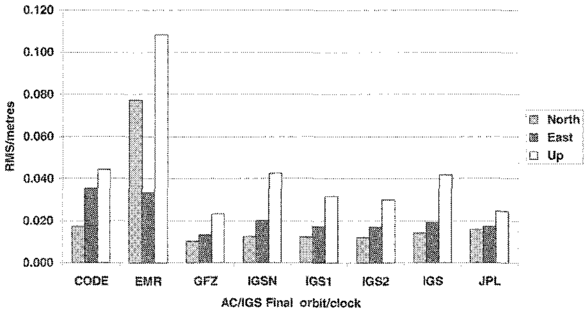

FIGURE 3. RMS of static GIPSY ppp (AUCK, BRUS, USUD and WILL, GPS wk 995) with AC/IGS orbits not corrected for origin offsets; the IGS orbits plus the new clock combinations: IGSN—all 5 ACs; IGS1—ESA excluded; IGS2—ESA, COD excluded.

differences with respect to ITRF96 positions using orbits not corrected for daily orbit origin offsets. Here, most of the increase seen with respect to Figure 2 is due to the daily variations of AC and IGS orbit origins rather than due to smaller, station-specific, position biases that were constant during the week.

4. RECENT RESULTS

The new satellite/station clock combination has been running in an experimental modus since GPS wk 1042 for the IGS Final combinations and since GPS wk 1054 for the IGS Rapid combinations. The new clock combination produces, beside a clock RINEX file, a summary file that contains the overall results for each of the individual ACs, an example of this is shown in Table 1. This summary table gives, for each of the ACs, the number of epochs (NREPO) of their station/satellite clock solution, the number of epochs excluded from the combination (NBEPO), the number of clock solutions (NRCLK), and the number of excluded clock solutions (NRBAD). In addition, the offset and drift of each AC solution with respect to the combined solution are given here, as well as the RMS agreement between the AC and the combined clock solution (RMS). The last column gives the weight which the AC clock solution was given in the clock combination process. In addition to the summary table, shown in Table 1, for each individual AC the clock summary file contains the detailed information about the bias and RMS for every station and satellite. All these summary tables of the experimental clock analysis are made available on the anonymous ftp server at the Astronomical Institute of the University of Berne (ftp://ftp.unibe.ch/aiub/springer/clock).

In the Final and Rapid combination summaries, the results from both the old and the new clock combinations are used in the navigation quality control solutions. From these results, as in 1999, it is not clear that there is any quality difference between the two combined clock products. To better verify the quality of the current state of the new clock combination the static ppp test was repeated using data for GPS wk 1081 from the stations BRUS, TOW2, and WILL. One difference is that in this ppp test the Bernese GPS software package was used. These new ppp results are similar to the earlier results obtained for GPS wk 0995 but show a significant improvement of the overall quality. Except for COD and EMR the repeatability over the seven days were below the 10 mm, quite an impressive achievement. The

TABLE 1

Summary table of the new clock combination for GPS wk 1081 day 6

CEN	*NREPO*	*NBEPO*	*NRCLK*	*NRBAD*	*OFFSET (ns)*	*DRIFT (ns/d)*	*RMS (ns)*	*WEIGHT (%)*
cod	287	0	19956	340	0.06	0.37	0.09	18.01
emr	288	0	13081	273	−58.67	1.46	0.09	17.80
esa	288	0	17399	763	1590.11	24.92	0.11	13.14
gfz	288	0	21134	738	−0.20	-0.28	0.05	29.95
igr	288	0	17666	19	0.06	-0.13	0.08	0.00
igs	96	0	2591	11	−0.08	-0.06	0.03	0.00
jpl	288	0	15334	34	0.82	-0.50	0.07	21.10
ngs	96	0	2591	0	−0.06	-0.09	4.50	0.00

IGS Rapid satellite/station (igr), IGS Final satellite (igs), and NGS broadcast satellite (ngs) clock solutions are included for comparisons only (hence zero weights).

orbits from EMR still show significant daily origin variations. Since we did not account for these variations in this test series, the effects are clearly visible in the static ppp test results. The best repeatability is obtained for GFZ, and it is at the level of 1, 3, and 6 mm for North, East, and Up directions, respectively. This may be due to the fact that GFZ has implemented some Z-translation constraint in their final solutions, i.e., the GFZ Final, unlike the other AC Final solutions, are not truly minimally constrained. This constraint improves the stability of the GFZ orbits, which leads to the improved daily ppp repeatability when not accounting for the daily orbit origin variations. The results for the IGS (old), IGC (new), and IGR clocks were comparable to those of ESA and JPL and are at the 3-, 4-, and 7-mm level. Interestingly the results from the IGS Rapid (IGR) clocks were better than both IGS and IGC. This is most likely caused by the fact that the IGR orbits are constrained (computed using a fiducial station strategy) and hence the orbits have smaller daily origin variations. This is also shown in the 1999 IGS Technical Report (Springer et al., 2000). Although no significant quality difference is observed between the old and new clock combination it is clear that we have reached the millimeter level consistency for the IGS orbit, clock, ERP, and SINEX products, even without accounting for the daily origin variations.

5. SUMMARY AND OUTLOOK

The new station and satellite clock combination algorithm has been developed and extensively tested. The new clock combination maintains orbit/clock consistency at millimeter level, which is comparable to the best AC orbit/clock solutions. As has been demonstrated by the static ppp result tests with the GIPSY and Bernese software packages, the millimeter ppp repeatability level, which is comparable to the best AC orbit/clock solutions, is achieved with the new IGS orbit/clock combinations.

The only problem remaining is the small variation of the IGS Final orbit origin. Although the origin is consistent with ITRF at the millimeter level, the daily millimeter variations are still visible in the static ppp tests. The daily origin variations are the consequence of the minimal constraint approach adopted for the IGS Final orbit/clock solutions. The IGS Rapid orbit/clock and GFZ Final solutions show much smaller origin variation (especially in the Z-direction). This is likely because the IGS Rapid orbit/clock solutions are constrained and GFZ Final solutions apply constraints in the Z-origin component. To mitigate this origin variation effect, which currently (GPS wk 1081) is a much lesser issue than it was in GPS wk 0995, the IGS Final orbit/clock combinations could be enhanced also to maintain the IGS orbit origin at the millimeter level, e.g., by using the static ppp results.

Since the new combinations have performed well during the test period of about 40 weeks, at the 2000 AC Workshop, held at the US Naval Observatory in Washington, DC, it has been decided that the new IGS clock combination would become official starting on the GPS week 1087 (5 November 2000). At that time the old clock combinations will be discontinued and only the new clock combination will be used from there on. ■

REFERENCES

Beutler, G., Kouba, J., & Springer, T.A. (1995). Combining the orbits of the IGS Analysis Centers. Bulletin Geodesique, 69, 200–222.

Dow, J.M., Kouba, J., & Springer, T.A. (Eds.). (1998). Proceedings of 1998 IGS Analysis Center Workshop, Darmstadt, Germany, 9–11 February 1998, European Space Centre of the European Space Agency.

Ferland, R. (1999). Densification of ITRF. Reference Frame Working Group Report. In 1998 IGS technical reports (pp. 219–222). Pasadena, CA: Jet Propulsion Laboratory.

Kouba J., Mireault, Y., & Lahaye, F. (1995). 1994 IGS orbit/clock combination and evaluation. Appendix I of the Analysis Coordinator Report. In IGS 1994 Annual Report (pp. 70–94). Pasadena, CA: Jet Propulsion Laboratory.

Kouba, J., Ray, J.R., & Watkins, M.M. (1998). IGS Reference Frame realization In J.M. Dow et al. (Eds.), Proceedings of 1998 AC Workshop (pp. 139–172). Darmstadt, Germany, 9–11 February 1998, European Space Centre of the European Space Agency.

Ray, J.R. (1999). IGS/BIPM Time Transfer Project. GPS Solutions, 2(3), 37–40.

Springer, T.A., Zumberge, J.F., & Kouba, J. (1998). The IGS analysis products and consistency of combined solutions. In J.M. Dow et al. (Eds.), Proceedings of 1998 AC Workshop (pp. 37–54). Darmstadt, Germany, 9–11 February 1998, European Space Centre of the European Space Agency.

Springer, T.A., Kouba, J., & Mireault, Y. (in press). 1999 Analysis Coordinator Report. IGS 1999 Technical Report. Pasadena, CA: Jet Propulsion Laboratory.

Zumberge, J.F., Heflin, M.B., Jefferson, D.C., Watkins, M.M., & Webb, F.H. (1997). Precise point positioning for the efficient and robust analysis of GPS data from large networks. Journal of Geophysical Research, 102(B3), 5005–5017.

Zumberge, J., & Gendt, G. (2000). The demise of selective availability and implications for the International GPS Service. Position paper presented at the IGS Network Workshop 2000.

BIOGRAPHIES

Jan Kouba, DrSc, has been working in satellite geodesy since 1970. During 1994–1998 he was the first IGS Analysis Center Coordinator. Although he retired from his active duties at the Geodetic Survey Division of Natural Resources Canada in April 1998 and from the IGS Gov-