AOS STUDIES ON GNSS TIME TRANSFER

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Abstract

The AOS during last decade conducted intensive works on use of GPS, GLONASS, and other GNSS, for high accuracy time transfer. This resulted in developing of several prototypes of GNSS time receivers. Until recently, AOS-type receivers were most often used for multichannel C/A codes time transfer. But recent developments allowed P3 and PPP applications. This paper provides details of P3 computation for GPS and GLONASS, as well as details of PPP time transfer using GPS RINEX files, and IGS and ESA ephemerides and clock products.

INTRODUCTION

This paper presents analysis of the GPS and GLONASS timing data in several modes: GPS AV C/A, GPS and GLONASS P3, and GPS PPP. Data were delivered in CGGTTS and Rinex formats by two receivers, TTS-3 and TTS-4 developed by the Space Research Centre AOS Borowiec team. All calculations in P3 mode were performed by means of BIPM Tsoft software **[1]**. Data used for the computations cover the time period 1-31 May 2010. The calculations in PPP mode were performed using two different packages: the BIPM’s Tsoft and Bernese GPS Software v.5.0 **[2]**. In the case of PPP mode, various sets of data were analyzed: a 5-day set of data for 9-14 June 2010 (Tsoft solution) and 7-day set of data for 24-31 October 2010 (Bernese solution). The P3 analysis concerns GPS and GLONASS data provided by the TTS-4 receivers. The PPP analysis concerns only GPS data from TTS-3 and TTS-4 receivers.

Additionally, the comparison between GPS P3 and GPS AV were done for five laboratories for the period 1-31 May 2010. Also, a comparison of the Standard Product 3 format (sp3) files delivered by ESA and IGS containing the satellites clock corrections were performed. Such a comparison allows evaluation of the difference between ESA’s and IGS’s products and its impact on time transfer.

The results presented in this paper show the quality of the data produced by TTS receivers and permit further development and improvement of their performance that may contribute to the enhancement of time transfer by various GNSS systems.

TIME TRANSFER SYSTEM

The Astrogeodynamical Observatory in Borowiec (AOS) of Space Research Center, following a very successful TTS-2 and TTS-3, has developed a new high-performance Time Transfer System 4 (TTS-4). TTS-4 is a new generation receiver allowing all available GNSS methods of time transfer. The receiver is capable of carrying on observations on the L1, L2, and L5 frequencies for GPS, the L1 and L2 frequencies for GLONASS, and the L1 and E5 frequencies for Galileo. At this moment, the observations of the Giove-A and Giove-B are supported. For the time transfer, ionosphere-free linear combination of P1 and P2, called P3, is provided for GPS and GLONASS. Also, both carrier-frequency and code measurements are available in the RINEX format for GPS and GLONASS.

Basic features of the TTS-4 receiver are:

- GPS and GLONASS C/A-code, GPS and GLONASS P-code modes
- Integrated observations of all available navigation satellites; GPS, GLONASS, WAAS, and EGNOS, and in the future Galileo. At this moment, observation of the Giove-A and Giove-B are supported
- 116 channels (all-in-view): GPS L1-16, GPS L2/L2C-16, GPS L5-16, Galileo E1-16, Galileo E5A-16, GLONASS L1-16, GLONASS L2-16, SBAS-4
- Observation data in CGGTTS commo- view format for GPS and GLONASS:
    - L1 data (C/A and reconstructed P-code) [L1C, L1P]
    - L2 data (C/A and reconstructed P-code) [L2C, L2P]
    - L3 ionosphere free combination (C/A and reconstructed P-code) [L3C, L3P]
    - L5 data (GPS, reconstructed P-code) [L5P]
- Observation data in RINEX format (code and phase data). Supported observation types: L1, L2, L5, C1, C2, P1, P2, P5, D1, D2.

The system is controlled by LINUX, providing multitasking and integration with networks. The functional diagram of the receiver is presented on Figure 1.

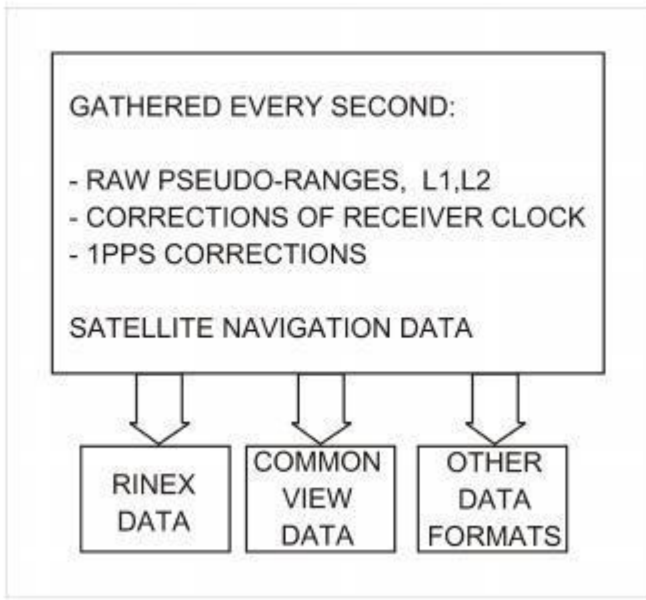

Figure 1. Functional diagram of the Time Transfer System.

The performance of the TTS-4 system depends on the antenna used. TTS-4 may be equipped with the standard choke-ring or thermostabilized choke-ring antenna. The performances of the choke-ring antennas are up to 2 times better then standard one. There are two operational modes for the GNSS timing receivers:

1) The TTS-4 receiver with new software is operated with the internal clock synchronized to the local laboratory reference time scale by a phase lock (using 1PPS and an external reference frequency 3-30 MHz). In this mode, the receiver time scale is coherent with the local reference time scale. There is no need for a time-interval counter.

2) For the TTS-3 and TTS-4 receivers with the early software versions installed, the GNSS module clock is synchronized to local reference time by the use of a time-interval counter.

Both methods have some advantages and disadvantages.

P3 TIME TRANSFER

The first study of the AOS laboratory concerns the P3 mode using the dual-frequency code observables for both GPS and GLONASS **[3,4]**. In this paper, the P3 results for time link AOS-PTB are presented. All computations were performed by means of BIPM Tsoft program **[1]** using Vondrak smoothing. The data cover the time period 1-31 May 2010. The results are shown on Figures 2 and 3. Each of these figures reports: the time link AOS-PTB, the differences between the raw measured value and the smoothed, the Modified Allan deviation, and the time deviation.

In the case of GLONASS solution, the scatter of the residuals is about two times bigger than for GPS solution. The sigmas are 0.527 and 1.413 ns for GPS P3 and GLONASS P3, respectively. Performance of TTS receivers for GPS P3 is similar or better than other types of time receivers.

Additionally, the comparisons between GPS P3 and GPS AV were done for five laboratories AOS (Borowiec), LV (Riga), NIS (Cairo), UME (Gebze-Kocaeli), and PTB (Braunschweig) for the period of 1-31 May 2010 in 5-day intervals with use of the Tsoft package. All these laboratories are equipped with TTS receivers. The calculations were performed for the following time links: AOS-PTB, LV-PTB, NIS-PTB, and UME-PTB. Results are presented in Table 1.

Table 1. Difference between GPS P3 AV and GPS C/A AV for TTS receivers for the time links between AOS, LV, NIS, UME, and PTB, expressed in ns.

MJD	AOS	LV	NIS	UME	
55319	-13.4	-17.1	-16.4	-5.7	
55324	-11.6	-17.4	-16.5	-5.5	
55329	-12.5	-18.3	-16.5	-6.1	
55334	-11.6	-17.6	-16.2	-4.5	
55339	-11.7	-17.0	-16.2	-5.6	
55344	-11.4	-16.8	-15.7	-4.2	
	-12.0	-17.4	-16.3	-5.3	Avg. /ns
	0.8	0.5	0.3	0.7	Sigma /ns

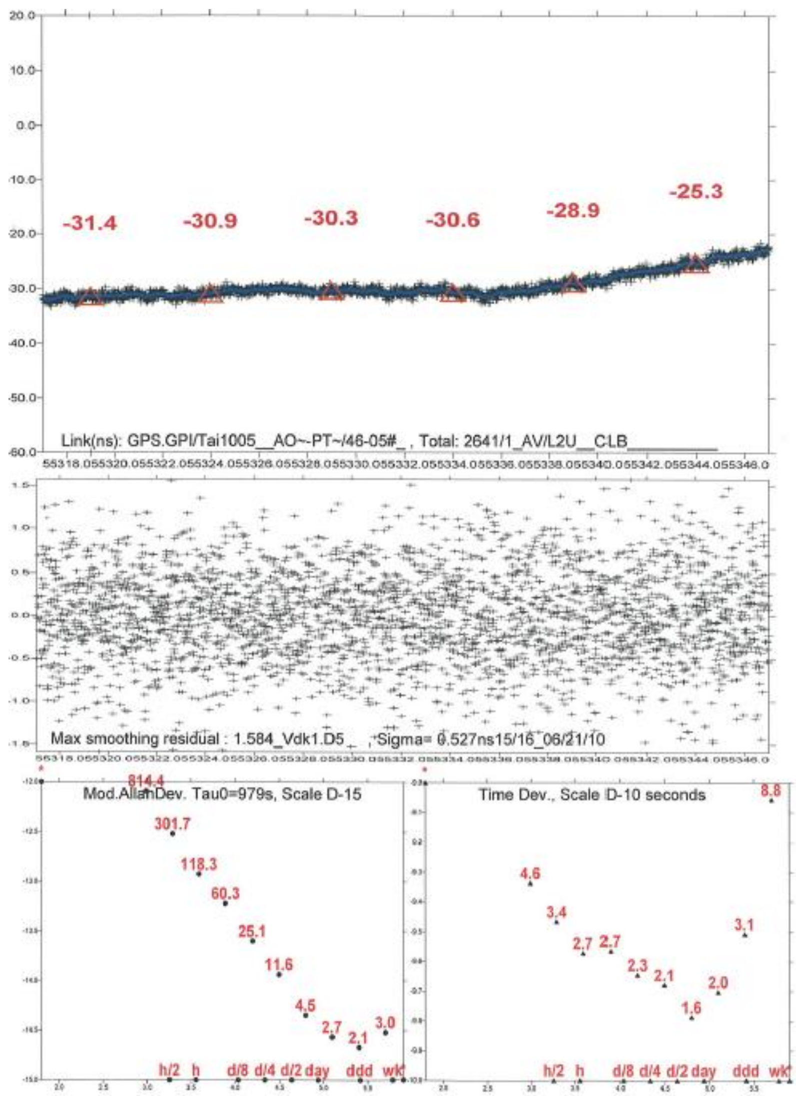

Figure 2. GPS P3 mode results for time link AOS-PTB in a 1-month period (May 2010).

The mean values of the GPS P3-GPS C/-code differences change in a range of -5.3 to -17.4 ns. They are due to inconsistency in calibrations, and are easy to remove by an appropriate calibration exercise. The sigmas of the comparison between GPS P3 AV and GPS C/A AV vary from 0.3 to 0.8 ns, which shows excellent consistency.

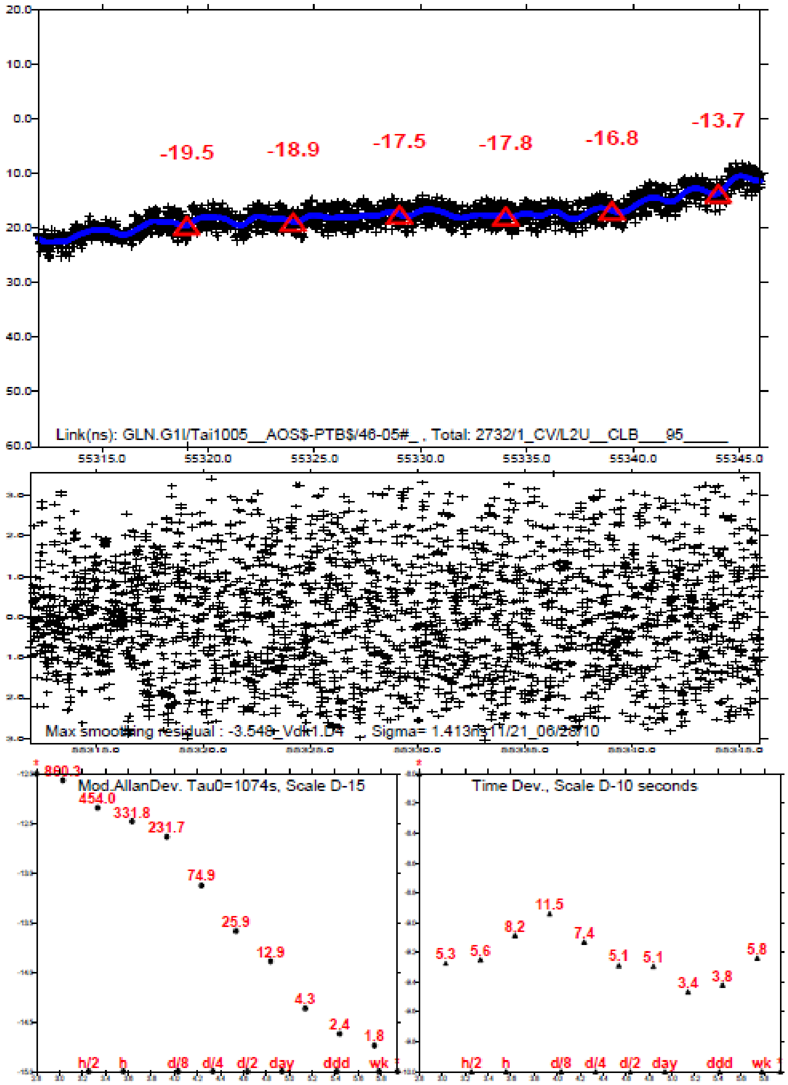

Figure 3. GLONASS P3 mode results for time link AOS-PTB in a 1-month period (May 2010).

PPP TIME TRANSFER

One of the techniques used for TTS receivers data analysis is PPP (Precise Point Positioning). This technique evolved in the last few years and has become a very important tool for precise station coordinates and station clocks determination for a single GNSS receiver. An advantage to the PPP approach is that the position of the receiver is estimated with cm precision and receiver clock parameters can be estimated with sub-ns precision, even if the receiver is not part of a network of stations **[5-7]**.

In this work, the PPP technique was used for TTS receiver time transfer and receiver clock estimations. All calculations were performed with two programs: BIPM's Tsoft **[1]** and Bernese GPS Software **[2]**, and were based on precise satellite orbits, satellite clocks, and updated pole files produced by the IGS.

In the first step, the calculations were performed for 5-day sets of data for 9-14 June 2010. All data for this period come from three different TTS-4 receivers (110, 113, 116). The configuration of the receivers is presented in Table 2.

Table 2. Configuration of the Time Transfer Systems for the PPP mode.

Receiver sn.	Receiver type	Antenna type	Software/ Hardware/ Firmware
110	TTS-4	JAV_GRANT-G3T	2.7.7/133/22
113	TTS-4	JNSMARANT_GGD	2.7.5/133/19
116	TTS-4	JAV_GRANT-G3T	2.7.7/133/22

The clocks of the receivers were synchronized to the 1PPS signals and referenced to the same frequency of an atomic clock standard (Active H-maser CH1-75A), which is used for the realization of UTC time scale at the AOS. The TTS-4 AOS data were compared with the PTB TTS-3 data (AOS-PTB link). In this study, BIPM Tsoft program was used for estimation of two parameters:

- smoothed value of the comparison between AOS and PTB time scales in nanoseconds
- RMS of the this comparison in nanoseconds.

The results are presented on Figure 4, 5, and 6.

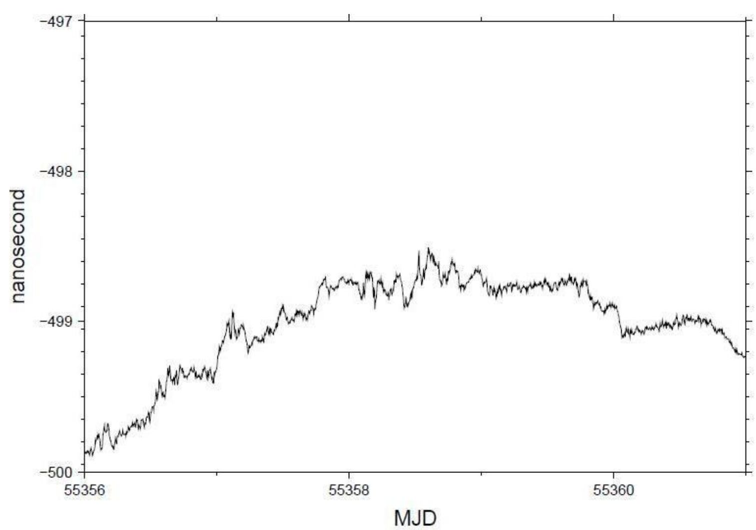

Figure 4. Time transfer in PPP mode between AOS and PTB for 5-day sets of data for 9-14 June 2010 for the TTS-4 receiver sn 110.

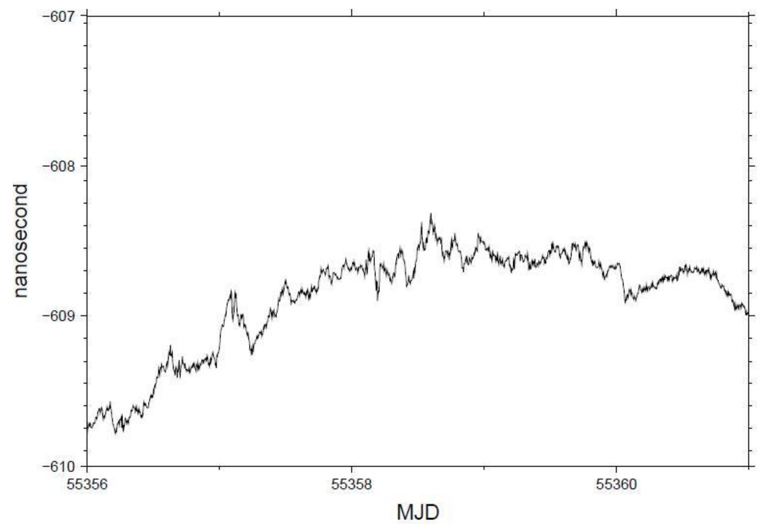

Figure 5. Time transfer in the PPP mode between AOS and PTB for 5-day sets of data for 9-14 June 2010 for the TTS-4 receiver sn. 113.

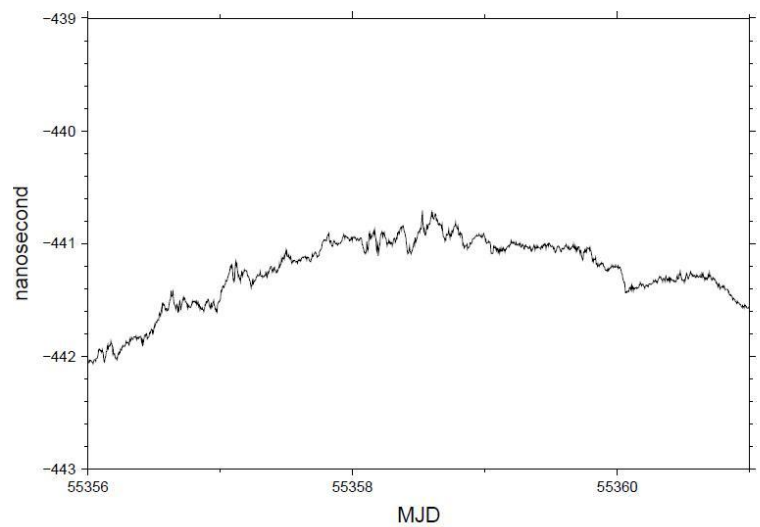

Figure 6. Time transfer in PPP mode between AOS and PTB for 5-day sets of data for 9-14 June 2010 for the TTS-4 receiver sn. 116.

The RMS's for these solutions are 0.323, 0.349, and 0.305 ns respectively, performance similar to other types of geodetic time receivers. The constant differences between TTS-4 receivers at the AOS of the order of a few hundreds of nanoseconds are due to lack of calibration, which will be carried out at the beginning of 2011.

A FIRST TEST OF BERNESE GPS SOFTWARE FOR PPP PROCESSING AT AOS − ONE-SITE CLOCK CORRECTION COMPARISON

The AOS has undertaken work on an autonomous use of Bernese GPS Software **[2]** in PPP mode for time transfer. In a first attempt, a test of one-site clock correction computation and comparison was conducted for a 7-day sets of data for 24-31 October 2010. Each day constitutes one file of 24-hour data. The data were recorded with 30-second intervals. All data for this period come from two TTS receivers, TTS-3 and TTS-4 at the AOS. Table 3 shows the differences in configuration between the two receivers.

Table 3. Differences in configuration between TTS-3 and TTS-4 for the PPP mode.

Receiver name	Receiver type	Antenna type	Software/ Hardware/ Frimware
VIRGO	TTS-3	JNSMARANT_GGD	1.125/80/6
SN_120	TTS-4	JNSMARANT_GGD	2.8/133/19

The clocks of these receivers were synchronized to the 1PPS signals and referenced to the same frequency of an atomic clock standard at AOS. A short description and statistics of analyzed data are shown in Table 4.

Table 4. Characteristic of the data.

MJD	TYPE OF OBSERVATIONS	FREQUENCY	NUMBER OF OBSERVATIONS TTS-4	NUMBER OF OBSERVATIONS TTS-3
54493	P/C	L3	46008	47964
54494	P/C	L3	45906	48066
54495	P/C	L3	46118	48068
54496	P/C	L3	45996	47898
54497	P/C	L3	45622	48332
54498	P/C	L3	45794	48138
54499	P/C	L3	45448	47796

The calculations were performed by means of Bernese GPS Software with the standard PPP procedure (static mode) with the use of phase and code observations in the ionosphere-free linear combination mode L3.

In this study two parameters were estimated:

- estimated corrections of the clock values in nanoseconds

- RMS for the estimated parameters in nanoseconds.

The results are shown on Figures 7 and 8.

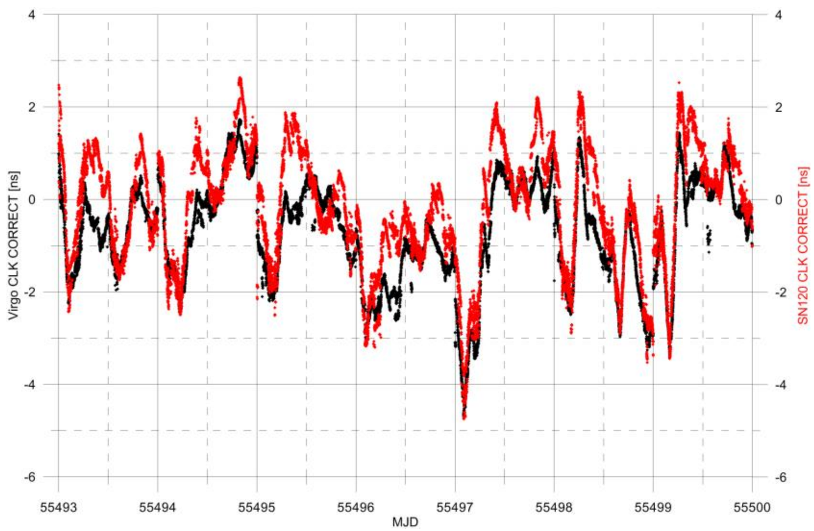

Figure 7. Estimated corrections of the clock values in nanoseconds (black line – TTS-3, red line – TTS-4).

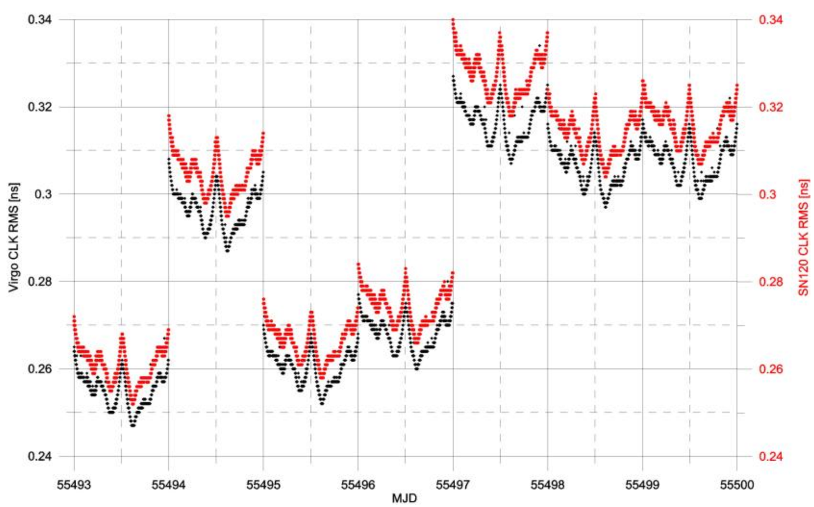

Figure 8. RMS for the estimated parameters in nanoseconds (black line – TTS-3, red line – TTS-4).

In Table 5, the mean values with the RMS of the estimated clock corrections were collected for 1-day and 7-day analyzed data periods. For the TTS-3 receiver, the mean correction of the clock is -0.734 ns and for the TTS-4 receiver it is -0.170 ns. The scattering of the estimated clock corrections results is greater for the TTS-4 receiver for both the 1-day and 7-day solutions.

Table 5. The mean estimated clock corrections.

MJD	TTS-3				TTS-4			
	1-day		7-day		1-day		7-day	
	Avg. /ns	RMS /ns	Avg. /ns	RMS /ns	Avg. /ns	RMS /ns	Avg. /ns	RMS /ns
54493	-0.661	0.640	-0.734	1.115	-0.079	0.950	-0.170	1.267
54494	-0.100	1.052			0.301	1.207		
54495	-0.560	0.722			0.022	0.957		
54496	-1.559	0.606			-0.972	0.766		
54497	-0.752	1.603			-0.086	1.683		
54498	-1.282	1.021			-0.682	1.328		
54499	-0.222	1.003			0.310	1.168		

A very interesting effect is shown in Figure 8. The RMS of the estimated parameters are different for each day. Also, for the full analyzed period, the RMS for the TTS-4 receiver is a little bit worse than the RMS for the TTS-3 receiver. Generally in all cases, the RMS of the estimated clock corrections is from 0.24 to 0.34 ns.

SATELLITE ORBIT AND CLOCK CORRECTIONS COMPARISON

Another AOS study was dedicated to the comparison of satellite clock corrections produced by ESA and IGS in form of orbit solution *sp3* files.

The *sp3* files from ESA and IGS centers can be downloaded from public ftp server *ftp://cddis.gsfc.nasa.gov*. The clock corrections were compared only for GPS satellites for the period 1-31 May 1 2010 (55317-55347 MJD). IGS produces the ephemeris files in several modes, *igp* (predicted), *igr* (rapid), *igs* (final), *igu* (ultra). For satellite clock corrections comparison, the *igr* and *igs* products were chosen. The rapid product is available with approximately a 17-hour latency and the final combinations are available at a 12-day latency. The accuracy of the rapid and final products for GPS satellites are on the same level of 2.5 cm and 75 ps for orbits and satellite clocks, respectively.

Table 6 presents status and the difference in content of ESA's and IGS's *sp3* files for the analyzed period.

Table 6. Satellites status in *sp3* files produced by ESA and IGS.

Satellites	ESA	IGR	IGS
GLONASS	+	-	-
GPS PRN01	-	+	+
GPS PRN25	-	-	-

ESA's files contain satellite clock corrections also for GLONASS, but GLONASS data are not available for *igr* and *igs* files.

In all files, the data for GPS PRN25 satellite are not available. In the case of ESA's files, the data for GPS PRN01 satellite are missing. The satellite clock corrections were compared for a four GPS satellite sample. The results are shown in Table 7.

Table 7. GPS satellite clock correction comparison for ESA and IGS products.

GPS Sat.	Number of clock correction comparisons	ESA-IGR		IGR-IGS	
		Avg. /ns	Sigma /ns	Avg. /ns	Sigma /ns
PRN02	2976	0.394	0.647	-0.017	0.041
PRN03	992	0.516	0.678	-0.044	0.047
PRN04	1905	0.424	0.660	-0.023	0.042
PRN05	408	0.578	0.640	-0.008	0.045

The IGR-IGS solution differences are in the range 0.01-0.05 ns with an RMS of about 0.04 ns. The computation of the GPS PPP AOS-PTB time link was performed for the 5-day period 9-14, 2010. The difference between ESA's and IGS' *sp3* products has a mean value of 0.005 ns and the RMS equals 0.043 ns. Although this difference is worth notice, up to now, it does not have a practical meaning for the time transfer.

In the case of ESA-IGR comparison, the differences are much larger: from 0.4 to 0.6 ns with an RMS at the level of 0.6-0.7 ns, which is significant for PPP processing. In Figure 9, the results of PPP calculations for the AOS-PTB time link using ESA's and IGR's *sp3* files are shown.

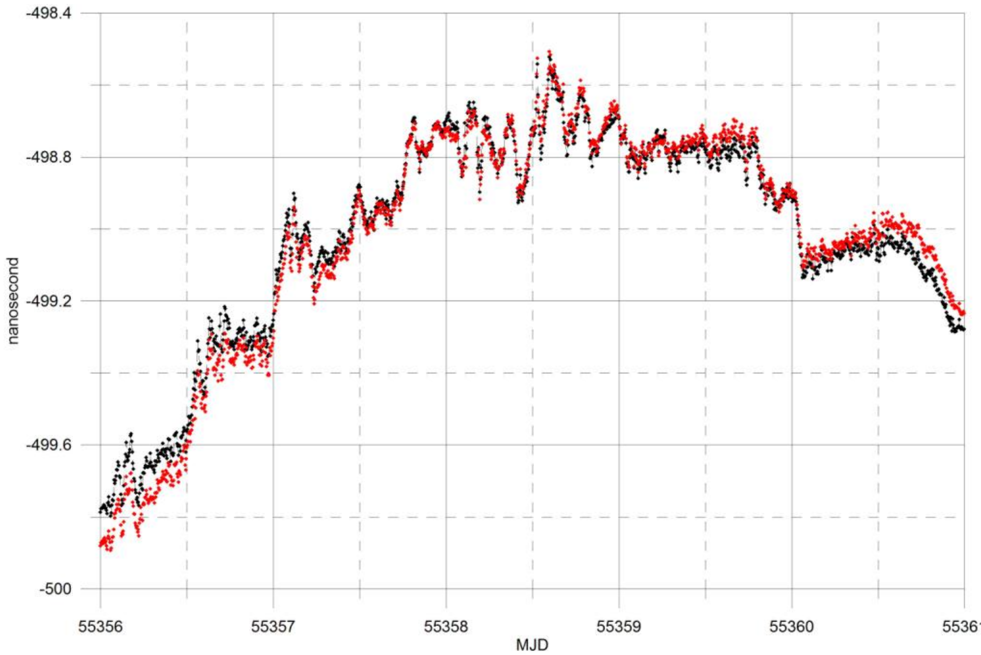

Figure 9. PPP processing by Tsoft package for the AOS-PTB time link for the period of 9-14 June 2010 based on ESA (black dots) and IGR (red dots) ephemeris files.

CONCLUSIONS

This paper presents studies, problems, and results of the work performed at the AOS during the last year on GPS AV C/A, GPS and GLONASS P3, and GPS PPP data obtained from Time Transfer System receivers developed by the AOS. One of the goals is permanent development and improvement of the Time Transfer Systems, but first of all, the enhancement of the AOS time transfer performance and its contribution to the Polish time scales UTC (AOS), UTC (PL), and TA (PL) to the Galileo system time infrastructure and to international time metrology. Actually, work has been started on the new generation of the GNSS Time Transfer System (TTS-5) – at present. the operational generation is the TTS-4 receiver. Current functions of TTS-4 enable the following time transfer methods: operational GPS Common-View (GPS CV) and GPS All-In-View (GPS AV) for both C/A and P3 codes, operational GLONASS Common-View (GLONASS CV) for C/A, P and P3 codes, GPS and GLONASS PPP, and experimental Galileo Common View (Galileo CV).

The PPP is the best performing time transfer GNSS technique, and is an excellent tool for the evaluation of other most advanced methods of time transfer such as TWSTFT and T2L2. The first results of GPS PPP obtained by the AOS presented in this paper are similar to other laboratories using this method (sigma of about 0.3 ns), and promise further progress.

GPS P3 results presented in this paper have the same quality or better (RMS 0.5 ns) as that obtained from other types of timing receivers.

Further planned works at the AOS include:

- improvement of the GLONASS P3 showing poor performance in this study
- development of GLONASS PPP
- development of GPS and GLONASS PPP data processing packages
- work on combined solutions for GPS+GLONASS **[8]**
- calibrations of GPS and GLONASS PPP, TWSTFT, and T2L2
- calibrations of GLONASS frequency biases **[9]**
- Galileo and Chinese COMPASS Common-View experiments.

The AOS has developed a unique ensemble of time transfer techniques, and probably is the only laboratory equipped with GPS, GLONASS, Galileo (soon COMPASS), TWSTFT, and T2L2 time transfer methods. This presents exclusive conditions for research work on time transfer. One of the results is a contribution to the maintenance of the UTC (AOS) to within ± 10 ns from UTC. The AOS is also the reference laboratory for publishing, in Section 5 of BIPM *Circular T*, the time scale broadcast by GLONASS **[10]**.

ACKNOWLEDGMENTS

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