USE OF GLONASS AT THE BIPM

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Abstract

The Russian Navigation Satellite System (GLONASS) provides interesting opportunities for international time metrology. The GLONASS constellation is now in the final stages of construction and can already be used for international time transfer. At least 19 national time laboratories are now equipped with the most recent GPS/GLONASS time receivers. The BIPM collects data from these receivers and is now publishing related time links. GLONASS links are now compared on a regular basis to GPS links and will also soon be compared to TWSTFT links. This paper reports the latest results from the BIPM.

INTRODUCTION

Over the last 50 years, the accuracy of atomic clocks has improved by an order of magnitude every 7 years. Today, in metrology, we are witnessing the birth of a number of new and innovative frequency standards. These devices have accuracy of about 1 part in 10^{15} and seem to have short-term instability approaching 1 part in 10^{16}. This corresponds to a clock having the capability of maintaining a level of performance corresponding to 10 picoseconds/day. As the newest devices are not transportable and do not operate continuously, it is important to be able to compare them within a reasonable length of time in order to determine the existence of systematic differences. A measurement with a precision of 1 nanosecond over a 24-hour period corresponds to 1×10^{-14} in frequency. Therefore, at today's present levels, it would take weeks to compare two such devices. That is why it is important to develop and improve time transfer methods to allow these comparisons to be made within a reasonable length of time. For this reason, the timing community is devoting much effort to the development of new approaches to time and frequency comparisons. Among them are global navigation satellite system (GNSS) techniques based on multi-channel GPS and GLONASS C/A-codes, P-codes, and carrier-phase measurements, temperature-stabilized antennae, and standardization of receiver software.

One of the newest approaches to time and frequency comparisons consists of using GLONASS (Global Navigation Satellite System) C/A-code and P-code. Use of GLONASS in standard CGGTTS Common-View mode was proposed in 1996 **[1,2]**, has been the object of several studies **[3-5]**.

GLONASS system time is steered to the Russian representation of UTC to keep the system time within 1 microsecond of UTC (SU). But unlike *GPS time*, *GLONASS time* follows UTC seconds, so it is not a continuous time scale. Unfortunately, during adjustments for leap seconds, access to GLONASS signals is subject to discontinuities. This creates some problems, but does not have a significant impact on the use of GLONASS for time metrology. In fact, GLONASS is the only GNSS complying with all international recommendations related to UTC, although is paying for this as mentioned above.

In this paper, we report on *GNSS time* recording at the BIPM, and especially on *GLONASS time*. Next, we describe calibration of the GLONASS time links, and computation of GLONASS Common-View (CV) time links and their comparison with GPS All-in-View (AV) time links. Finally, we describe the introduction of GLONASS CV time links into the computation of TAI/UTC.

GNSS SYSTEM TIMES

All the GNSSs rely on precise time to enable precise ranging measurements for positioning, where the requisite is intra-system consistent synchronization. They maintain internal system times to provide this navigational service, and these system times do not need to be related to external standards. System times are formed using system clock ensembles. They may be steered to an external time scale considered to be the reference maintaining constraints on their maximum tolerated departure.

This is the case of *GPS time*, which follows UTC modulo 1 second via its local representation UTC (USNO) maintained at the U.S. Naval Observatory (USNO) (see Figures 1-3). *GPS time* is continuous and is not adjusted for leap seconds. It is currently 15 seconds ahead of UTC within a precision limit of less than tens of nanoseconds.

GLONASS time is steered to the Russian representation of UTC to keep the system time within 1 microsecond of UTC (SU) (see Figure 2). However, unlike *GPS time*, *GLONASS time* follows UTC seconds, so it is not a continuous time scale. Unfortunately, during adjustments for leap seconds, access to GLONASS might be subject to discontinuities. It should be noted that the *GLONASS time* receivers were not calibrated absolutely, and their readings have an accuracy only of some hundreds of seconds.

Safe operation of GNSS requires system times that should preferably not apply UTC leap seconds **[6]**. This request is causing major difficulties to designers of GNSS, as there is not an ideal solution for choosing a reference epoch for numbering seconds. The upcoming systems – such as Japanese QZSS, Chinese BEIDOU, and COMPASS, and Indian GAGAN and IRNSS – face similar difficulties.

It should be stressed that system times are pseudo-time scales, which are not dedicated for metrological applications. They should be regarded as being internal technical parameters, and not as reference time scales.

However, the GNSS represent by far the most widely available means to obtain accurate UTC; GPS and GLONASS respectively disseminate corrections to their system time to obtain UTC (USNO) and UTC (SU). Galileo will also broadcast a physical realization of UTC, as will probably the other GNSS.

The recording and publishing of *GPS time* and *GLONASS time* in *BIPM Circular T* **[7]** are reported in Figures 1 and 2.

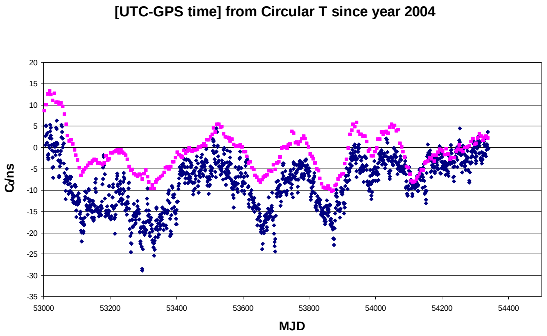

Figure 1. [*UTC-GPS time*] (in blue) and [*UTC-UTC(USNO)*] (in pink) from *Circular T* since the year 2004.

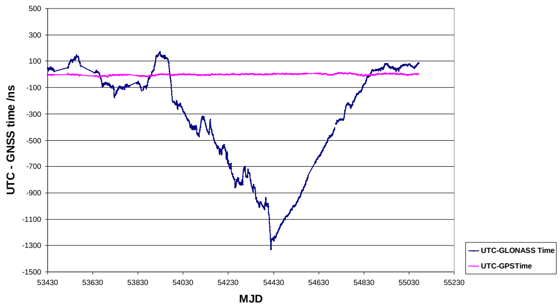

Figure 2. Values of [*UTC-GPS time*] (in pink) and [*UTC-GLONASS time*] (in blue) from *Circular T* since the year 2004.

Concerning *Galileo System Time* (GST), we address here only the numbering of seconds and not the other characteristics of GST. From the very beginning of the Galileo project, it was decided that GST should fulfill all international recommendations **[6]**; however, like *GPS time*, it should be a continuous time scale without leap seconds.

At first, the use of TAI was considered as reference for GST. However, there was concern that in this way GST would become the unique physical realization of TAI. This could lead to confusion, as TAI was never intended for broadcasting. Finally, for the sake of interoperability with GPS, it has been decided that GST will have the same numbering of seconds as *GPS time* (see Figure 3).

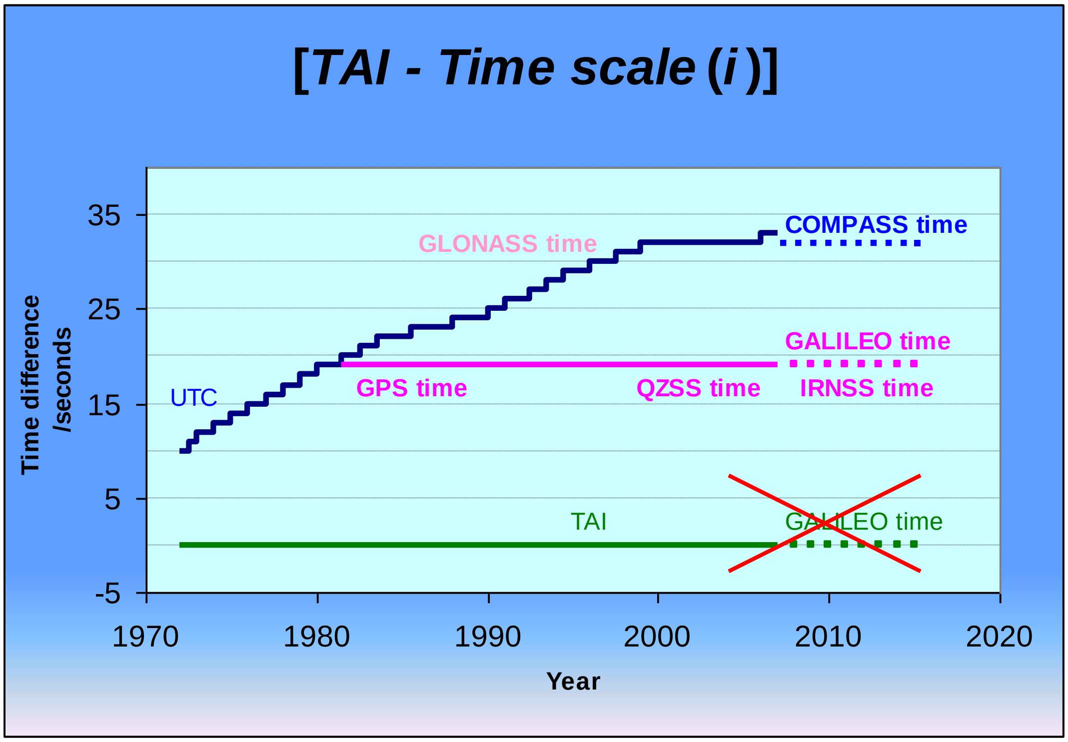

Figure 3. [*TAI – Time scale (i)*] for UTC, *GPS time*, *GLONASS time* and *Galileo time* (differences in seconds). Note change of definition of *Galileo time*.

Table 1. Differences in seconds between various GNSS times TAI, and UTC in November 2009 (differences smaller than 1 s are neglected).

GPS time: steered to UTC(USNO) modulo 1s
 [*TAI – GPS time*] = 19 s
 [*UTC – GPS time*] = – 15 s
GLONASS time: steered to UTC (SU) with leap seconds
 [*TAI – GLONASS time*] = 34 s
 [*UTC – GLONASS time*] = 0 s
Galileo time: steered to a set of EU UTC (k) modulo 1 s, using GPS time seconds
 [T*AI – Galileo time*] = 19 s
 [*UTC – Galileo time*] = – 15 s
COMPASS time: will be steered to set of Chinese UTC (k) modulo 1 s
 [*TAI – COMPASS time*] = 33 s
 [*UTC – COMPASS time*] = – 1 s

GLONASS STATUS

The first GLONASS satellite was launched in 1982. By November 2009, 19 satellites were in orbit, of which 16 were operational and three were in maintenance. The full 24-satellite constellation is expected to be operational within a couple of years. The GLONASS time reference is described in the previous section. Its reference frame is PZ-90, which is designed to be closely aligned to the International Terrestrial Reference Frame (ITRF). GLONASS has been declared by the Russian Federation government to be dual-use (civil and military) technology.

The GPS and GLONASS systems share basically the same concept. However, a substantial difference between them lies in their signal structure. GPS uses Code Division Multiple Access (CDMA): every satellite transmits the same two carriers modulated by PRN-codes particular to each satellite. GLONASS uses Frequency Division Multiple Access (FDMA): two individual carrier frequencies are assigned to each satellite, but the PRN-codes are the same for all satellites.

Both GPS and GLONASS have freely accessible C/A-code that modulates L1 only. Like the GPS precision code, the GLONASS P-code modulates both carriers, but unlike GPS P-code Anti-Spoofing (AS), GLONASS P-code is freely accessible. The GLONASS P-code offers two main advantages for high-precision time transfer. Firstly, the GLONASS P-code modulation on both L1 and L2 carrier frequencies allows high-precision measurements of ionospheric delays. Secondly, the GLONASS P-code chip rate is one-tenth that of the GLONASS C/A-code and one-fifth that of the GPS C/A-code. This means that GLONASS P-code pseudo-range measurements are much more precise than GPS C/A-code or GLONASS C/A-code measurements.

Today, in its final stages of construction, the GLONASS constellation can already be used for operational international time transfer.

CALIBRATION OF GLONASS TIME LINKS

It should be noted first that, in this study, delay differences introduced by the different GLONASS frequencies have been neglected. This is possible as, in modern GLONASS time receivers, unlike in older ones, these differences are small **[8]**.

To differentially calibrate GLONASS time links, we use previously calibrated GPS links. Figures 4 and 5 show GPS and GLONASS links before and after GLONASS calibration. After calibration of GLONASS against GPS, mixing of GPS and GLONASS common-view data is possible (see Figure 5), but this is not main object of this study.

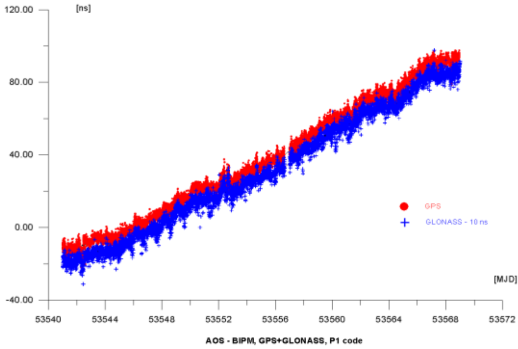

Figure 4. Comparison of clocks between AOS and BIPM, distant by 1200 km, using GPS and GLONASS time transfer.

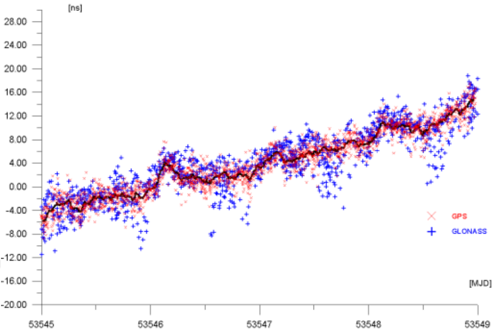

Figure 5. Comparison of clocks between AOS and BIPM, distant by 1200 km, using GPS+GLONASS P1-code time transfer technique, rms = 1.8 ns.

For this study, and for considered operational use of GLONASS for TAI, we have compared the time link SU/PTB computed by calibrated GPS AV links and the uncalibrated GLONASS CV link for May 2009. SU represents the time service of the National Research Institute for Physicotechnical and Radio Engineering Measurements (VNIIFTRI) located in Mendeleevo near Moscow, Russian Federation, and PTB represents the time service of the Physikalisch-Technische Bundesanstalt, located in Braunschweig, Germany. The two sites are separated by about 1800 km. Both sites use the same double-system GPS/GLONASS time receivers. The links were calculated under the conditions described below.

The difference between the two techniques was initially 92.5 ns, and the GLONASS CV link was, therefore, corrected by this value. The results are reported in Table 2.

Table 2. Differences between GLONASS CV and GPS AV before and after applying the calibration correction for the SU/PTB link in May 2009.

UTC (SU) – UTC (PTB)	**(*GLONASS CV – GPS AV*) /ns**	
	Mean	**rms**
Before calibration	**– 92.5**	**0.9**
After calibration	**– 0.0**	**0.9**

GLONASS COMMON-VIEW TIME TRANSFER

Nineteen laboratories are now equipped with double-system GPS/GLONASS time receivers.

The computation of GPS and GLONASS links for this study was conducted under the following conditions:

- Only C/A-code was used
- ESA precise ephemerides, clock correction, and IGS ionospheric maps were applied to GLONASS/GPS CGGTTS data
- Ground GPS/GLONASS antennae and precise ephemerides were expressed in the ITRF
- No GLONASS frequency delay calibration
- Differential calibration of GLONASS CV link by a GPS AV calibrated link
- Data collected for 5 months: May - September 2009.

To evaluate the quality of the GLONASS time links, we computed both GLONASS CV and GPS AV for links between the PTB (Germany) and: SU (Russian Federation), Astro-geodynamical Observatory (AOS, Poland), and Ulusal Metroloji Enstitüsü (UME, Turkey). These three GLONASS links were calibrated against GPS, as described in the previous section. The results for SU/PTB and AOS/PTB are detailed in Figure 6, and mean differences between GLONASS and GPS for the three links are summarized in Table 3.

Table 3. Comparison of GLONASS CV versus GPS AV for May-September 2009.

Link	**Mean(*GLN* – *GPS*) /ns**	**σ(GPS) /ns**	**σ(GLN) /ns**	**σ(*GLN* – *GPS*) /ns**	**Baseline /km**
AOS-PTB	**– 0.2**	**0.9**	**1.3**	**1.8**	**400**
SU-PTB	**– 0.2**	**1.1**	**1.0**	**1.2**	**1800**
UME-PTB	**– 0.3**	**1.3**	**1.4**	**1.3**	**1900**

The Type A uncertainty of GLONASS C/A CV links is similar to that of GPS C/A AV for baselines up to 2000 km. Calibrated GLONASS CV time links match the GPS AV links to within a few hundreds of picoseconds. Comparison carried out over 5 months proves the stability of both the GPS and GLONASS calibrations. The SU/PTB GLONASS CV link was introduced into the *BIPM Circular T* in November 2009.

In Tables 4a and 4b, we report excerpts from *BIPM Circular T* for October 2009 and November 2009, showing the switch from the SU/PTB GPS AV link to the SU/PTB GLONASS CV link. It is seen that the uncertainty of the link is unchanged.

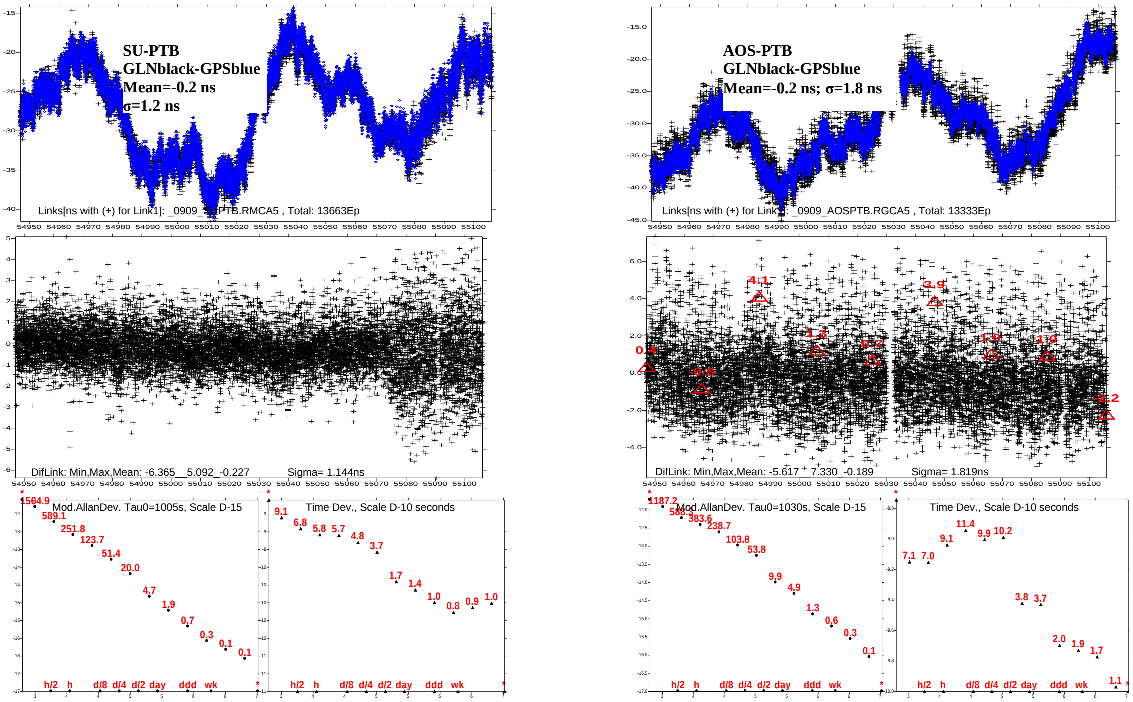

Figure 6. Comparison of GLONASS CV to GPS AV for the SU/PTB and AOS/PTB links during a 5-month period (May-September 2009).

Table 4a. Excerpt from *BIPM Circular T* Section 6 of October 2009.

Link	Type	uA/ns	uB/ns	Calibration Type	Calibration Dates
AOS/PTB	GPS AV	1.5	5.0	GPS EC/GPS EC	2007 Jan/2006 Sep
SU /PTB	GPS AV	1.5	5.0	GPS EC/GPS EC	2008 Sep/2006 Sep
UME /PTB	GPS AV	1.5	7.0	GPS EC/GPS EC	2005 Dec/2006 Sep

Table 4b. Excerpt from *BIPM Circular T* Section 6 of November 2009.

Link	Type	uA/ns	uB/ns	Calibration Type	Calibration Dates
AOS/PTB	GPS AV	1.5	5.0	GPS EC/GPS EC	2007 Jan/2006 Sep
SU /PTB	GLN CV	1.5	5.0	LC(GPS AV)	2009 May
UME /PTB	GPS AV	1.5	7.0	GPS EC/GPS EC	2005 Dec/2006 Sep

CONCLUSIONS

We have demonstrated the state-of-the-art of GLONASS time transfer at the BIPM. The Type A uncertainty of GLONASS C/A CV links is similar to that of GPS C/A AV for baselines up to 2000 km. A 5-month comparison with GPS proves the stability of the GLONASS calibration. GLONASS links and link comparisons to GPS have been available since May 2009 on the BIPM ftp site: *ftp://tai.bipm.org/TimeLink/LkC/*. In November 2009, a GLONASS CV, for SU/PTB, was introduced into the computation of TAI for the first time.

In performing direct differential calibration of GLONASS time receivers, it is indispensable to use a portable GLONASS receiver. Absolute calibration of GLONASS time receivers is essential for better evaluation of *GLONASS time* and GLONASS broadcasting of UTC (SU).

FUTURE WORK

Our work continues with the following projects:

- Use of TWSTFT data for further link comparison studies (AOS, OP, and PTB)
- Computation of links to other laboratories equipped with double-system receivers
- Investigate different types of receivers
- Use of P-code signals
- Receiver calibration including frequency delays
- Differential calibration of GLONASS receivers using a portable receiver
- Computation of GPS + GLONASS Common-View links
- Use of GLONASS carrier phase
- Absolute calibration of GLONASS receivers
- Publication in Section 5 of *Circular T* of the differences between UTC and UTC (USNO) broadcast by GPS and UTC (SU) broadcast by GLONASS **[9]**.

ACKNOWLEDGMENTS

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REFERENCES

[1] W. Lewandowski, J. Azoubib, A.G. Gevorkyan, P.P. Bogdanov, J. Danaher, G. de Jong, and J. Hahn, 1997, *"First Results from GLONASS Common-View Time Comparisons Realized According to the BIPM International Schedule,"* in Proceedings of the 28th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, 3-5 December 1996, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 357-366.

[2] W. Lewandowski, J. Azoubib, G. de Jong, J. Nawrocki, and J. Danaher, 1997, *"A New Approach to International Satellite Time and Frequency Comparisons: 'All-in-View' Multi-Channel GPS + GLONASS Observations,"* in Proceedings of the 10th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION-GPS), 16-19 September 1997, Kansas City, Missouri, USA (Institute of Navigation, Alexandria, Virginia), pp. 1085-1091.

[3] J. Azoubib and W. Lewandowski, 2000, *"Test of GLONASS precise-code time transfer,"* **Metrologia, 37,** 55-59.

[4] W. Lewandowski, J. Nawrocki, and J. Azoubib, 2001, *"First use of IGEX precise ephemerides for intercontinental GLONASS P-code time transfer,"* **Journal of Geodesy, 75**, 620-625.

[5] P. Bogdanov, A. Gevorkyan, and V. Zholnerov, 1998, *“Results of RIRT’s comparisons via Glonass signals,”* in Proceedings of the 30th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 1-3 December 1998, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp 211-218.

[6] F. Arias and W. Lewandowski, 2007, *“Role of international time reference UTC in the definition of Galileo System Time,”* in Proceedings of the Symposium on Scientific and Fundamental Aspects of the Galileo Program, 2-4 October 2007, Toulouse, France.

[7] BIPM Circular T, *http://www.bipm.org/jsp/en/TimeFtp.jsp?TypePub=publication*

[8] A. Foks, W. Lewandowski, and J. Nawrocki, 2005, *“Frequency biases calibration of GLONASS P-code time receivers,”* in Proceedings of the 19th European Frequency and Time Forum (EFTF), 21-24 March 2005, Besançon, France,

[9] Recommendation CCTF 6 (2009), *“Relationship of predictions of UTC(k) disseminated by Global Navigation Satellite Systems (GNSS) to UTC and TAI.”*