IGS

SESSION 4

TIME AND TIME TRANSFER

Recent Progress in Time Metrology and a Role for GLONASS

Wlodzimierz Lewandowski
Bureau International des Poids et Mesures
Pavillion de Breteuil, F-92312 Sèvres Cedex, France

Abstract

GPS is a navigation system that has proven itself to be a reliable source of positioning for both the military community and the civilian community. But, little known by many, is the fact that GPS has proven itself to be an important and valuable utility to the timekeeping community (Klepczynski, 1996). GPS is a versatile and global tool which can be used to both *distribute time* to an arbitrary number of users and *synchronise clocks* over large distances with a high degree of precision and accuracy. Similar performance can be obtained with the Russian global navigation satellite system GLONASS. This paper reports on recent progress in time and frequency transfer and focuses on combined use of GPS and GLONASS for time metrology.

Introduction

For the timekeeping community, GPS is today a significant contributor to solving the traditional problems of timekeeping; it is a reliable source of time and it is a reliable time transfer system (Klepczynski, 1996). The Russian global satellite navigation system GLONASS although not as well known as the GPS possesses comparable capabilities for navigation, precise geodetic positioning and time-transfer applications (Gouzhva et al., 1992). During the last few years time and frequency comparisons of remote atomic standards knew several interesting developments involving two systems which led to significant improvements which will be described in this paper (Lewandowski et al., 1997).

The introduction of GPS brought about a significant improvement in time and frequency transfer. With uncertainties ranging from 10 ns to 20 ns for time comparisons during early stages of the use of GPS, it was possible, for the first time, to compare the best atomic standards in the world at their full level of performance using integration times of about 10 days. Since then a number of improvements have been introduced, including the use of ultra-accurate antenna coordinates, precise ephemerides and measurements of the ionosphere. These led at the beginning of the 1990s to time comparison uncertainties of about 3 ns, which corresponds to a few parts in 10^{14} in frequency transfer. This paralleled improvements in atomic standards, which advanced by an order of magnitude, and made possible the comparison of the new clocks, e.g., HP5071A Cesium Beam Frequency Standards, at their full level of performances for averaging times of several days. The international time scales, International Atomic Time (TAI) and Coordinated Universal Time (UTC), are based on data from some 220 atomic clocks, the majority of them being HP5071A, located around the world in about 50 time laboratories. These time scales are computed by the Time Section of the Bureau International des Poids et Mesures (BIPM). At present the sole operational means of the comparing these clocks is the GPS Common-View technique based on C/A-code single-channel measurements. Use of GLONASS, introduced into time metrology on the experimental basis, at the beginning of the 1990s led to similar performances for continental links. Intercontinental GLONASS links were affected by lack of postprocessed precise ephemerides.

Today, in metrology, we are witnessing the birth of a number of new and innovative frequency standards. These devices seem to be approaching $1x10^{-15}$ in accuracy and seem to have short term instability approaching $1x10^{-16}$. This corresponds to a clock having the capability to maintain a level of performance corresponding to 10 picoseconds/day. Since the newest devices are not transportable and do not operate continuously, it is important to compare them in a reasonable time in order to determine the existence of systematic differences among them. A measurement with a precision of 1 nanosecond over a 24 hour period corresponds to $1x10^{-14}$ 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 amount of time. For this reason the timing community is engaged in the development of new approaches to time and frequency comparisons. Among them are techniques based on multi-channel GPS C/A-code measurements, GPS carrier-phase measurements, temperature-stabilised antennas and standardisation of receiver software. This paper focuses mainly on the progress which has resulted from the use of GPS and GLONASS multi-channel observations.

The GPS and GLONASS are also outstanding tools for the dissemination of Coordinated Universal Time (UTC). As GLONASS is not affected by Selective Availability (SA) this presents some advantages. This paper also reports some outlines on this subject.

Why GLONASS?

The Russian Global Navigation Satellite System (GLONASS) was inaugurated in 1982 and is still under development. Because the GLONASS signal is free of Selective Availability (SA) and Anti-Spoofing (AS) and is available world-wide, it offers the international time metrology community a useful additional tool for high-accuracy time transfer. However, the use of GLONASS signals, which have characteristics similar to those of GPS, was restricted for a long time because no commercial time receivers were available. This has changed recently: new GLONASS time receivers are now readily available paper (Lewandowski et al., 1997).

The GLONASS constellation not only offers an additional 24 satellites and a C/A-code signal free of SA, but it is also broadcast using an unencrypted P-code signal, unlike the GPS P-code which is subject to Anti-Spoofing (AS) encryption. GLONASS P-code being transmitted on both L1 and L2 frequencies, allows high-precision ionospheric delay measurements.

Originally GLONASS signals were broadcast on 48 frequencies (in the future 24 frequencies) in contrast to GPS, which is broadcast on 2. This causes some difficulties with the delay biases, which vary with frequency. These, however, can be resolved, so the GLONASS system provides the net advantage that it is less vulnerable to intentional or unintentional jamming.

This, however, has changed as IGEX precise ephemerides became available to civil users at the end of 1998. This makes it possible to use GLONASS more efficiently for intercontinental time links (see for more detail Nawrocki et al, 1999). Other improvements will follow, among them rigorous transformation parameters between the WGS 84 reference frame used by GPS and the PZ-90 reference frame used by GLONASS.

Joining GPS and GLONASS

Use of GLONASS underlines the need for global navigation satellite systems to adopt common reference systems. Indeed GPS and GLONASS use different references for both space and time. This does not preclude interchangeable use of the 48 satellites composing theoretically the two constellations, but does complicate it. Geodetic reference frames used by GPS and GLONASS can differ by up to 20 m on the surface of Earth, and their reference time scales differed by about 35 μs (modulo 1s) at the beginning of January 1997. It happens that GPS already follows international standards, to within 10 cm for reference frame and 10 ns to 50 ns (modulo 1 s) for time reference, and its agreement with them is permanently improved. Until now GLONASS does not follow international standards for the reference frame but did introduce in 1997 several changes into its time scales. These followed a far-reaching and important recommendation issued in September 1996 by the 85th Meeting of the CIPM (Comité International des Poids et Mesures), recommending (CIPM, 1996):

- that the reference times (modulo 1 second) of satellite navigation systems with global coverage[*] be synchronized as close as possible to UTC,
- that the reference frames for these systems be transformed to be in conformity with the terrestrial reference frame maintained by the International Earth Rotation Service (ITRF),
- that both GPS and GLONASS receivers be used at timing centres.

This Recommendation specifies a basis for harmonizing GPS and GLONASS, which does not make GLONASS depend on GPS, or GPS on GLONASS, but requires that both

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[*] Such as Global Positioning System (GPS), Global Navigation Satellite System (GLONASS), International Maritime Satellite Organization (INMARSAT), Global Navigation Satellite System 1 (GNSS1), Global Navigation Satellite System 2 (GNSS2).

systems maintain their time and space references in agreement with international standards. Following this Recommendation, the Russian Federation agreed to improve the synchronization of its time scales with UTC. On 27 November 1996 a time step of 9000 ns was applied to UTC(SU) in order to make it approach UTC (see Figure 1). Next, on 10 January 1997 a frequency step was applied to GLONASS time to adjust its frequency to be close to that of UTC(SU). This was followed by a time step of GLONASS time of about 35,300 ns. Following these changes, Russian time scales differ from UTC by a few hundred nanoseconds. As GLONASS time is linked to UTC(SU) with an accuracy of only a couple of hundred of nanoseconds, it is linked to UTC with the same accuracy. Further adjustments of these two time scales with respect to UTC are expected. This development is a sign of good will and understanding.

Because GLONASS receivers are not calibrated absolutely we know [*UTC - GLONASS time*] to an accuracy no better than several hundreds of nanoseconds. GPS receivers are absolutely calibrated and [*UTC - GPS time*] is known with an accuracy of a tens of nanoseconds, mainly because of SA. It follows that GLONASS provides an average user with world-wide real-time dissemination of UTC, as produced by the BIPM, to an uncertainty no better than several hundreds of nanoseconds after the recent improvement of the synchronization between UTC(SU) and UTC. GPS does the same with uncertainty of several tens of nanoseconds.

Summing up, we note that persisting differences between Russian time scales broadcast by GLONASS and UTC affect real-time dissemination of UTC through GLONASS, and to some extent complicate the dual GPS + GLONASS navigation solution. However, this discrepancy does not affect common-view time transfer, because readings of the satellite clock vanish in the difference. Also the lack of absolutely calibrated GLONASS receivers can easily be overcome for common-view time transfer by differential calibration of receivers.

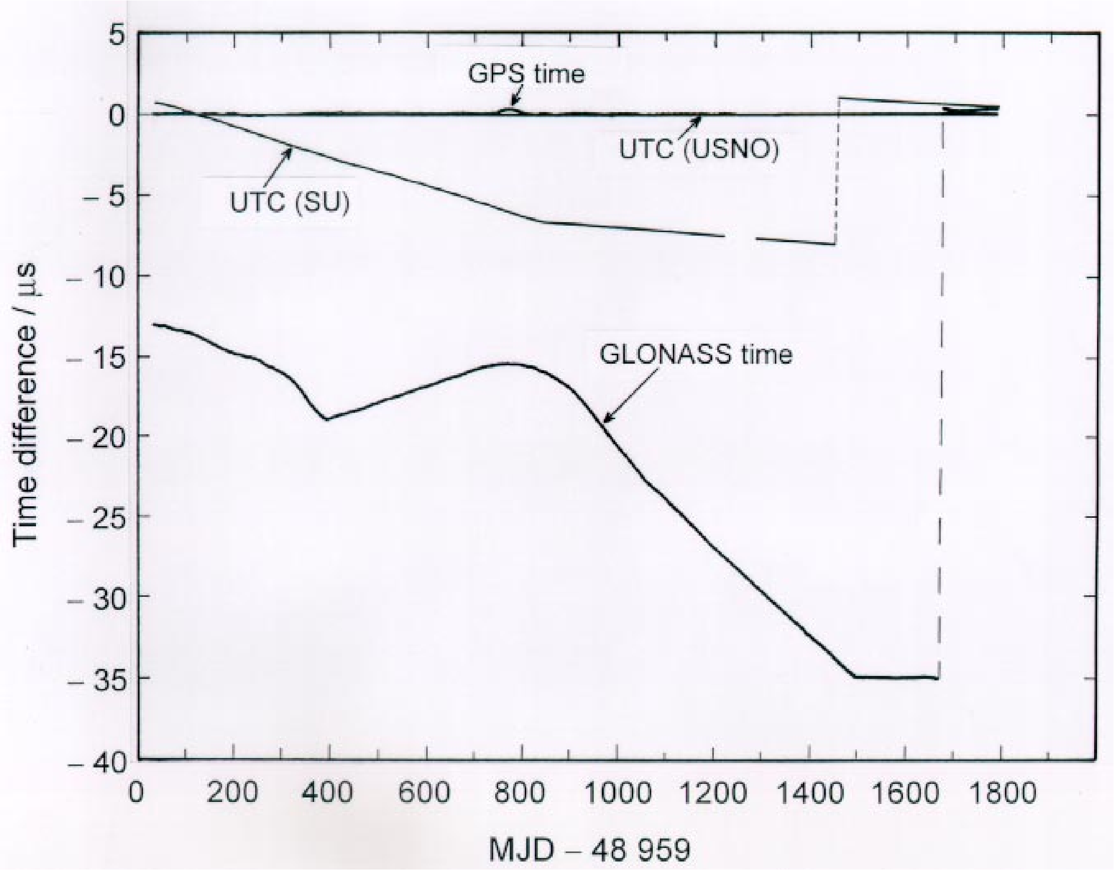

Figure 1. Deviation of UTC(USNO), UTC(SU), GPS time and GLONASS time from UTC from 3 December 1992 to 31 July 1997. For its time reference, GPS relies on UTC(USNO), Coordinated Universal Time (UTC) as realized by the USNO. GLONASS relies on UTC(SU), UTC as realized by the Russian Federation. UTC is produced by the BIPM and is the internationally recognized time reference.

New Type of Time Receivers

A resurgence in GPS time transfer has recently occurred because of the development and availability of multi-channel timing receivers which followed completion of the GPS constellation, reductions in receiver prices and requests from the timing community. For the previous fifteen years international time transfer had been carried out using single-channel C/A-code GPS receivers and an international common-view schedule of standard 13 minute tracks.

A few years ago the first commercial GLONASS two-channel time receivers became available. More recently new GPS + GLONASS multi-channel and multi-code time receivers have been developed. Already a number of major timing centres around the globe observe GPS and GLONASS in multi-channel and multi-code mode. Their receivers are all of type R-100/30, manufactured by 3S Navigation. These take the form of a 12-channel GPS + GLONASS C/A-code card, and two or more cards with GLONASS P-code channels. The number of GLONASS P-code cards can be increased.

Four to six satellites of each system can usually be observed simultaneously on the 12-channel C/A-code component of the receiver. Each receiver uses a single antenna. The receivers are controlled by a PC and use a standard format, developed for the GPS single-channel common-view technique by the CGGTTS, which has been adapted to suit two-system two-code multi-channel observations (Report of CGGTTS, 1997).

An important feature of all these receivers is that they also provide carrier phase measurements for GPS and GLONASS under a standard Receiver Independent Exchange Format (RINEX) (Gurtner, 1994). Carrier phase data is already used by these receivers to smooth GLONASS P-code measurements of the ionosphere. Data from these receivers recorded in RINEX format at about 15 sites around the world is used in the IGEX campaign. Data in RINEX format can possibly be used for carrier phase based techniques of frequency transfer now under development (the IGS/BIPM Pilot Project to Study Accurate Time and Frequency Comparisons Using GPS and Phase Measurements).

Multi-Channel Common-View C/A-Code GPS and GPS+GLONASS Time Transfer

The multi-channel C/A-code receivers considered here observe all GPS or all GPS+GLONASS satellites in view and use standard 13-minute tracks every 16 minutes at the standard hours. The multi-channel output data is stored in a single file in a standardized format (Report of CGGTTS, 1997).

Although, in theory, up to 12 GPS and 12 GLONASS satellites can be observed simultaneously, only about 5 GPS and 5 GLONASS satellites can be observed above 15° (and thus are of interest for time transfer) at an average urban site. As there are 89 useful 16-minute periods in a day, 89 tracks may be observed in each channel. Using all available observations above 15° (about 10 per 16-minute period), we may therefore observe 890 tracks per day. All these tracks may be used for regional common-view links. For very large baselines, between continents, about 200 daily common-view tracks may be available using a multi-channel approach.

The increase by a factor of twenty in the number of common views in the GPS+GLONASS multi-channel mode relative to the single-channel mode, should provide a consequent improvement in the quality of time and frequency transfer. A theoretical gain in stability of $(20)^{1/2} = 4.5$ is expected for averaging times where white phase noise is preponderant (Lewandowski et al., 1997).

Multi-channel observations, however, may be subject to systematic variations, mainly caused by environmental effects on the antenna. This should affect all channels in ways similar to those described above for single-channel receivers except for multipath effects. The gain obtained by multi-channel observations, and systematic effects, are illustrated by a trial comparison described thereafter.

The time link between the BIPM and the VSL considered in the trial comparison described here has a baseline of about 400 km. Both laboratories are equipped with R-100/30 receivers and their ground-antenna coordinates are expressed in the ITRF with an uncertainty of 0.3 m. At the time of our trial comparison neither receiver was equipped with a TSA antenna. At both laboratories, receivers were connected to HP5071A clocks. For this study we used data covering roughly 10 days. Both receivers were calibrated using a portable R-100/30 receiver (Azoubib et al., 1997). We observed a constant bias of 6 ns between the GPS and GLONASS links. After application of this correction, the GPS and GLONASS data could be mixed and we computed [*BIPM clock* - *VSL clock*] using GPS + GLONASS. Table 1 shows the number of common views available for the different kind of time link.

Table 1. Number of Common Views Per Day by Different Methods for [*BIPM clock* - *VSL clock*] Comparison

Method	Average number of common views per day	Average number of simultaneous common views
GPS Single-channel	38	1
GLONASS Single-channel	25	1
GPS Multi-channel	350	4.5
GLONASS Multi-channel	255	3.3
GPS+GLONASS Multi-channel	605	7.8

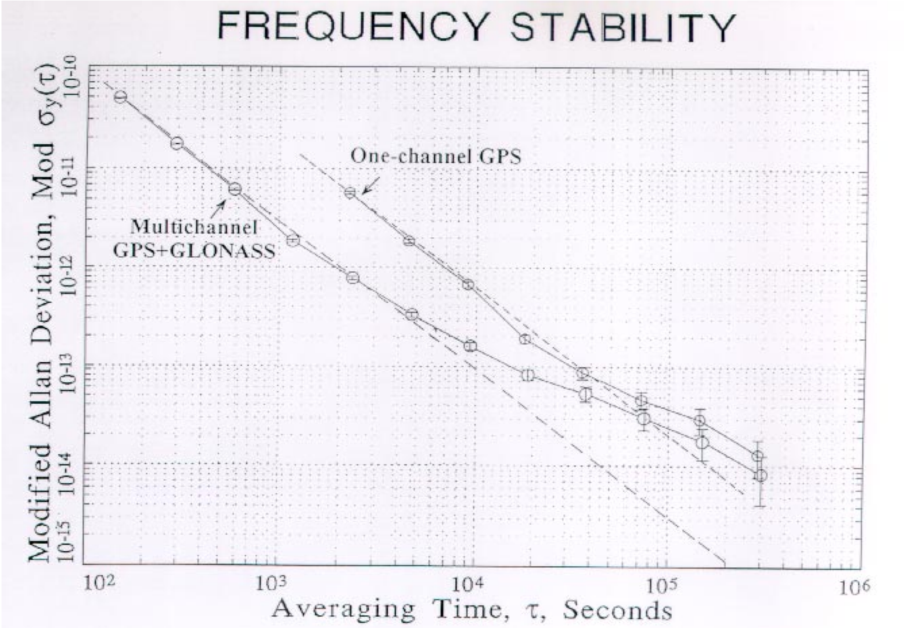

Figure 2. Modified Allan Standard Deviation of [*BIPM clock* - *VSL clock*] as given by single-channel GPS (1) and by multi-channel GPS+GLONASS (2) observations.

The level of noise for all these links is about 3 ns. However, we observe an important advantage obtained by increasing the number of daily common views from 38, for the single-channel GPS link, to the 605, for the multi-channel GPS + GLONASS link. A theoretical gain in stability of $(605/38)^{1/2} = 4$ is expected in the regions where white phase noise is preponderant. This can be seen on the stability curves of Figure 2 for averaging times of less than 10^4 seconds. Additional systematic effects are observed for averaging times above 10^4 seconds. These are probably linked to the environmental sensitivity of the antennas which were not temperature-stabilized.

Summary and Conclusions

GPS has become the workhorse of the timekeeping community. It is a source of time and can be used to compare clocks. Combining GPS and GLONASS code measurements within timing equipment receivers seems definitely to provide an additional value for international time comparisons. For GLONASS, the possibility of the access of precise code on two frequencies provides a means to measure ionospheric delays. Also, until recently, GLONASS signals were broadcast on 48 frequencies (in the future 24 frequencies) in contrast to GPS which is broadcast on 2. This provides a robust broadcasting system more resistant to interference.

GPS C/A-code time transfer, as now practiced, is limited mainly by hardware instabilities and, over long distances, by uncertainty in the determination of ionospheric delays. The uncertainty of single-channel comparisons is of 3 ns to 4 ns for one-day averaging times, sometimes larger. This is barely sufficient for the comparison of average commercial HP5071A clocks. This technique is obviously insufficient for the comparison of high performance laboratory frequency standards.

Increasing the number of daily common views by a factor of about 20 between a single-channel GPS link and multi-channel GPS + GLONASS link greatly improves the reliability of time transfer. A stability gain of 4 was observed between a single-channel GPS and a GPS + GLONASS multi-channel links for averaging times less than 10^4 seconds. Additional systematic effects were observed for averaging times above 10^4 seconds for 400 km and one-site comparisons. These are linked to the environmental sensitivity of the antennas. These systematic effects can be removed by using temperature-stabilized antennas providing, for integration times of one day, estimates of the frequency difference between remote atomic clocks with an uncertainty of a few parts in 10^{15}.

The receivers considered in this paper have the important feature that they record carrier phase measurements for GPS and GLONASS under standard RINEX format at the same time as they record standard 13 minute code measurements. The carrier phase data is already used to smooth GLONASS P-code measurements of the ionosphere and is used for the determination of GLONASS precise ephemerides during the IGEX campaign. It may also be used in carrier-phase based techniques for frequency transfer now under development. This underlines the universal character of these new types of receivers for the purposes of time metrology.

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Some Tests of GPS C/A-Code and GLONASS P-Code Time Transfers

J. Nawrocki
Astrogeodynamical Observatory of Borowiec
67-035 Kornik, Poznan 62-035, Poland

Jacques Azoubib and Wlodzimierz Lewandowski
Bureau International des Poids et Mesures
Pavillion de Breteuil, F-92312 Sèvres Cedex, France

Abstract

Most characteristics of the GLONASS signal are similar to those of GPS. In addition the GLONASS P-code, unlike the GPS P-code, is available to civil users and it is of great interest to take best advantage of it. GLONASS P-code pseudo-range measurements are considerably more precise than comparable GPS or GLONASS C/A-code measurements. In this paper we describe several tests of the GPS C/A-code and GLONASS P-code one-site comparison, and continental and intercontinental time transfers. Use of IGEX GLONASS precise ephemerides is commented on.

Introduction

Although not as well known as the GPS, the Russian global satellite navigation system GLONASS possesses comparable capabilities for navigation, precise geodetic positioning and time-transfer applications (Gouzha et al., 1992). During the last few years studies of time and frequency comparisons of remote atomic standards have seen several interesting developments involving GLONASS: C/A-code single-channel measurements led to performances similar to GPS for continental links; intercontinental links were affected by lack of post-processed GLONASS precise ephemerides (Lewandowski et al., 1997).

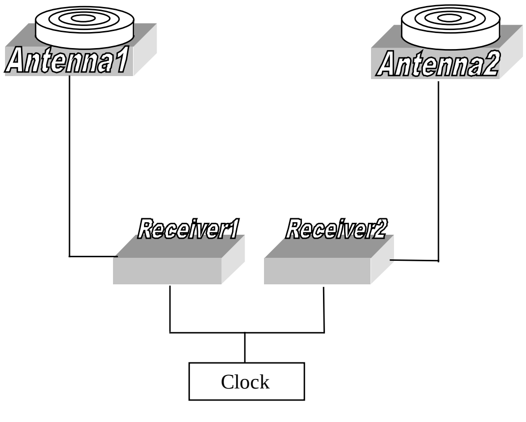
But the performance of single-channel GPS and GLONASS C/A-code common-view time transfer, with an uncertainty of about 3 ns, is barely sufficient for the comparison of current atomic clocks and needs to be improved rapidly to meet the challenge of the clocks now being designed. For this reason the timing community is engaged in the development of new approaches to time and frequency comparisons (Lewandowski and Azoubib, 1998; Lewandowski et al., 1999). Among them are techniques based on multi-channel GPS and GLONASS C/A-code measurements, GPS carrier-phase measurements, temperature-stabilized antennas and standardization of receiver software. In this paper we report on some tests of the GLONASS P-code. A one-site comparison shows that for single-channel GLONASS P-code time and frequency transfer a stability of 2 parts in 10^{15} is obtained over one day (200 picoseconds/day) (Azoubib et al., 1998a; Azoubib and Lewandowski, 1998; Azoubib et al., 1998b). These results indicate that GLONASS P-code time and frequency transfer in multi-channel mode should reach at least a stability of 1 part in 10^{15} over one day (100 picoseconds/day) for short baselines. We provide also the first tests of continental and intercontinental GLONASS P-code time transfer.

Advantages of GLONASS P-Code

The GLONASS P-code has two main advantages for precise time synchronization. First, GLONASS P-code has a chip length that is 1/10th that of GLONASS C/A-code and about 1/5th that of GPS C/A-code. This has the effect that GLONASS P-code pseudo-range measurements are considerably more precise than comparable GPS or GLONASS C/A-code measurements. Second, GLONASS P-code is transmitted on both L1 and L2 frequencies, so it allows high-precision ionospheric delay measurements.

GLONASS Frequency Biases

Originally GLONASS signals were programmed to broadcast on 48 frequencies (24 frequencies in the future) in contrast to GPS, which is broadcast on 2. This causes some difficulties with the delay biases, which vary with frequency (de Jong and Lewandowski, 1997). The spread of these biases across satellites can reach 15 nanoseconds and therefore mask other noise sources. Based on the data available so far, GLONASS frequency biases appear to be a function of temperature and relate to specific receivers. But once calibrated with respect to a reference receiver, and provided that temperatures are maintained via laboratory air-conditioning together with a temperature stabilized antenna (TSA), these values remain pretty constant and can therefore be determined and compensated in the software.



One-site configuration

Figure 1. Scheme of one-site comparison with two TSA antennas.

For the determination of GLONASS frequency biases, we use a one-site comparison of time receivers as described on Figure 1. Figure 2 shows one-site GLONASS P-code common-view values dt_i, for each track i, between two time receivers, for the GLONASS frequencies Nos. 1, 4 and 10. One can see clearly the biases between the values of dt_i resulting from the use of different GLONASS frequencies. For each GLONASS P-code frequency, the dispersion of the dt_i over the whole period computation is of the order 1 ns. We have arbitrarily chosen frequency no. 12 as a reference and then estimated a bias for each frequency *f*. Biases between local receiver and a travelling receiver were computed for the Observatoire Royale de Belgique (ORB) and for the Bureau International des Poids et Mesures (BIPM). Then biases between ORB and BIPM receivers were derived for each frequency *f* (see Table 1).

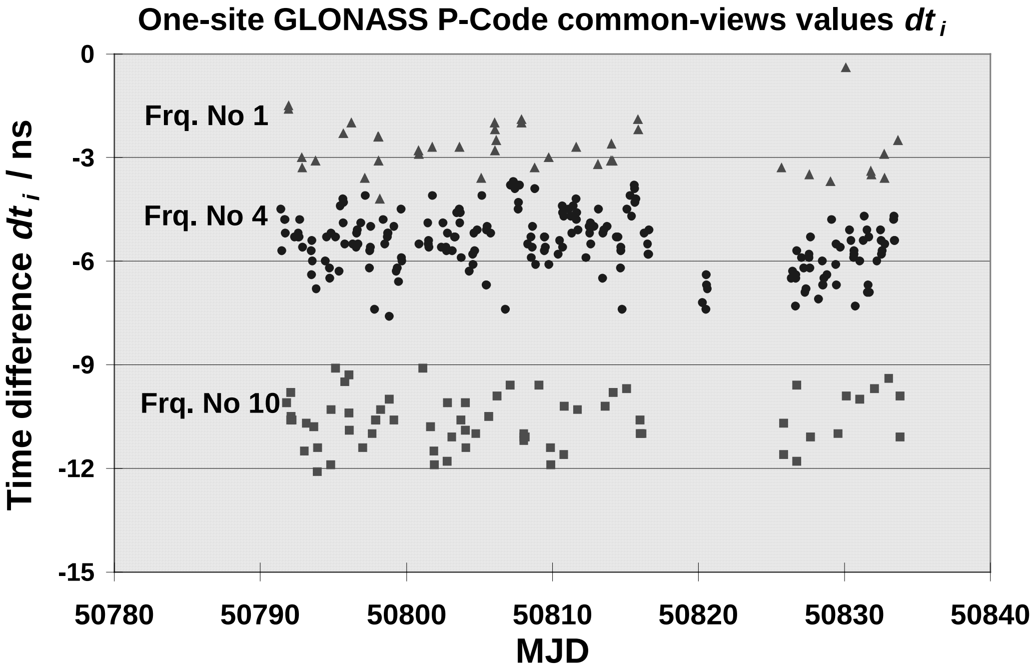


Figure 2. One-site comparison by different GLONASS P-code frequencies.

Table 1. Estimated Values of GLONASS P-code Frequency Biases for the Period of Evaluation Between Local and Travelling Receiver at the BIPM and ORB, and Between the BIPM and ORB Receivers

GLONASS P-Code frequency biases with respect to frequ. No 12

GLONASS Freq. No	Biases at ORB /ns	Biases at BIPM /ns	Biases ORB - BIPM /ns
1	1.1	4.3	-3.2
4	-3.0	2.5	-5.5
6	-3.8	1.6	-5.4
9	-1.5	0.6	-2.1
10	-0.7	0.4	-1.1
12	0.0	0.0	0.0
13	0.4	0.0	0.4
21	1.2	1.9	-0.7
22	-	2.2	-
24	1.7	3.7	-2.0

One-Site Comparison Test

In a one-site comparison test we demonstrate the improvement brought about by the use of GLONASS P-code for common-view time transfer by comparing the results with those obtained from GPS C/A-code common-view time transfer. During a calibration trip of GPS/GLONASS time equipment, we repeated this test in three locations: the BIPM, the Astrogeodynamical Observatory (AOS) and the ORB (see Figures 3 to 5). The three laboratories are equipped with TSA antennas. The travelling equipment comprises a GPS/GLONASS time receiver and a TSA antenna. After removing the bias specific to each GLONASS frequency the GLONASS P-code comparison shows outstanding performance at each of the three locations. All visited sites during this calibration trip are listed in Table 2.

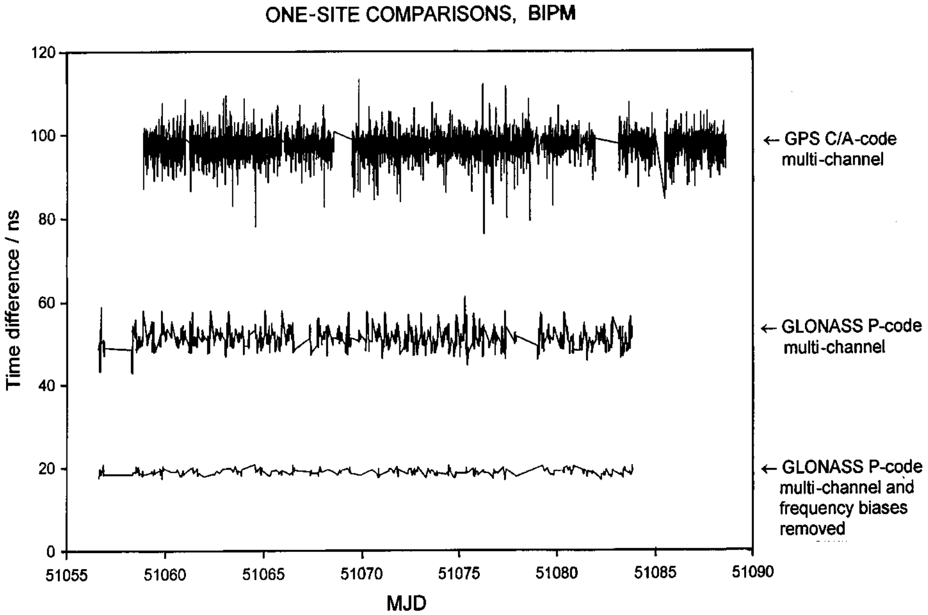


Figure 3. One-site comparisons at the BIPM (two separate TS antennas). Time differences between curves have no meaning; they were intentionally introduced for better reading.

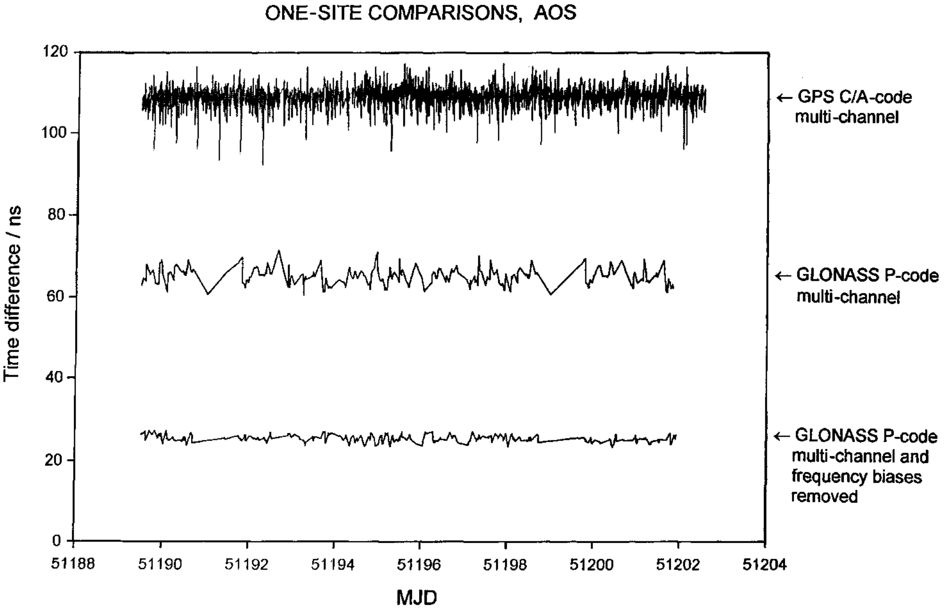


Figure 4. One-site comparisons at the AOS (two separate TSA antennas). Time differences between curves have no meaning; they were intentionally introduced for better reading.

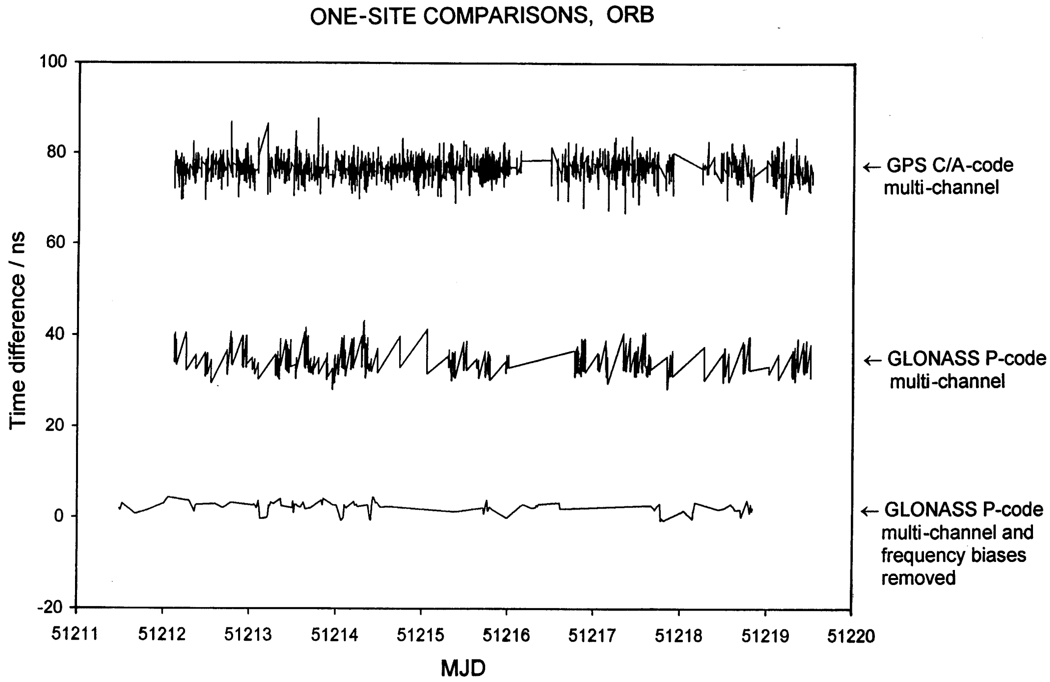


Figure 5. One-site comparisons at the ORB (two separate TSA antennas). Time differences between curves have no meaning; they were intentionally introduced for better reading.

Table 2. Schedule of the Calibration Campaign of GPS/GLONASS Receivers

16 July – 18 Nov. 1998	BIPM, France
29 Nov. – 16 Dec. 1998	OP, France
9 – 24 January. 1999	AOS, Poland
2- 15 February 1999	ORB, Belgium
17 Feb. – 1 March 1999	VSL, Netherlands
3 – 15 March 1999	NPL, UK
22 – 30 March 1999	IEN, Italy
7 - 19 April 1999	3S Navigation, USA
22 April – 3 May 1999	NIST, USA
7 – 17 May 1999	USNO, USA
21 May – 2 June 1999	CSIR, South Africa
8 – 21 June 1999	NML, Australia
28 June – 12 July 1999	CRL, Japan
19 – 29 July 1999	OP, France
30 July – 31 August 1999	BIPM, France

Time deviations of one-site comparisons at the BIPM were computed for four cases (Figure 6):

- GPS C/A-code single-channel without TSA antennas,
- GPS C/A-code multi-channel without and with TSA antennas,
- GLONASS P-code single-channel with TSA antennas and biases compensated for different GLONASS frequencies.

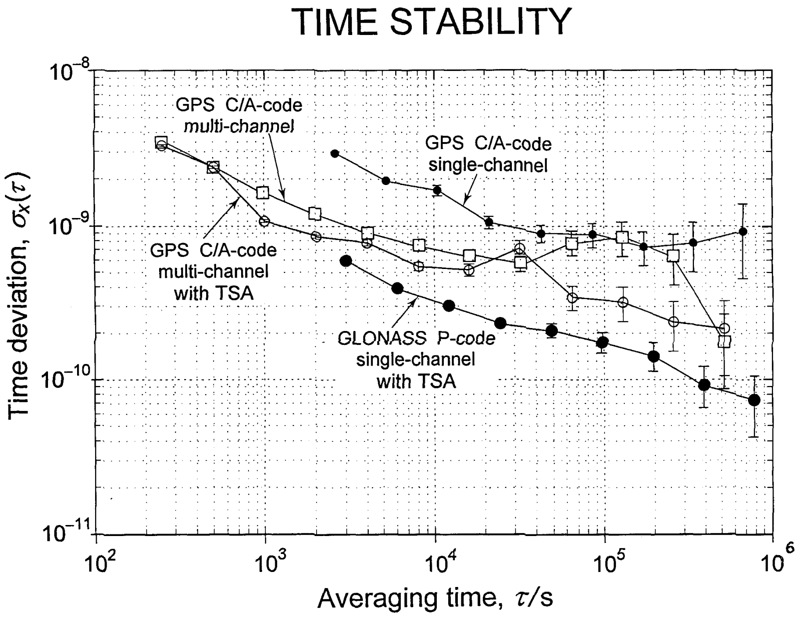


Figure 6. Time Deviation for one-site comparisons (two separate antennas on a single site).

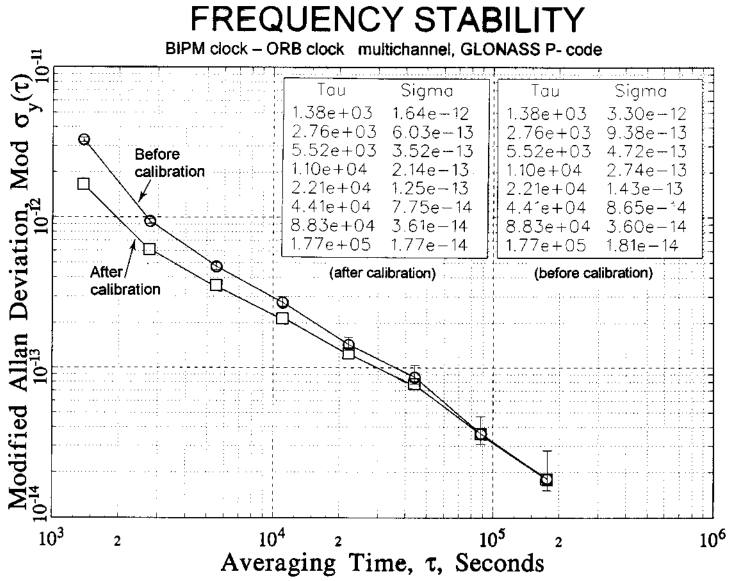
Except for the GLONASS P-code, the level of noise for the all the above comparisons is about 3 ns. The gain in stability between GPS C/A-code single-channel and a multi-channel comparison is in line with our expectations according to the considerations reported above. The multi-channel comparison without TSA antennas is affected by a systematic effect which becomes evident at about $3x10^4$ seconds. This effect is removed when the TSA antennas are activated. However, a smaller systematic effect with a period of several hours persists; this may have its origin in the antenna cables. Recent data from another pair of receivers of the same type equipped with TSA antennas exhibit no systematic effect.

After removing the bias specific to each frequency, the level of noise for the GLONASS P-code comparison using TSA antennas is about 600 picoseconds. The reduction in noise level between GPS C/A-code single-channel and GLONASS P-code single-channel comparison is about 5. The use of GLONASS P-code in multi-channel mode should provide an improvement in stability similar to that found for GPS C/A-code. Consequently, the expected time stability with an averaging time of one day should be several tens of picoseconds: this corresponds to a frequency stability of several parts in 10^{16}.

A 300 Km Time Transfer Test

A first test of continental GLONASS P-code time transfer over about 300 km between the ORB and the BIPM was conducted. GLONASS receivers at both locations were calibrated differentially using a portable receiver. The results are provided in Table 1.

The time transfer between the two locations was computed first without removing biases due to different GLONASS frequencies. Then differential time corrections provided by Table 1 were applied. We observe an improvement in frequency stability between non-calibrated and calibrated data as reported on Figure 7.



Tau	Sigma
1.38e+03	1.64e−12
2.76e+03	6.03e−13
5.52e+03	3.52e−13
1.10e+04	2.14e−13
2.21e+04	1.25e−13
4.41e+04	7.75e−14
8.83e+04	3.61e−14
1.77e+05	1.77e−14

(after calibration)

Tau	Sigma
1.38e+03	3.30e−12
2.76e+03	9.38e−13
5.52e+03	4.72e−13
1.10e+04	2.74e−13
2.21e+04	1.43e−13
4.41e+04	8.65e−14
8.83e+04	3.60e−14
1.77e+05	1.81e−14

(before calibration)

Figure 7. Frequency stability of [*BIPM clock – ORB clock*] compared by GLONASS P-code common view without calibration of GLONASS frequency biases and after calibration.

A 6000 Km Time Transfer Test

For GPS and GLONASS time transfer over several thousand kilometers, the use of post-processed precise ephemerides and ionospheric measurements is necessary to obtain the best results. In the case of GLONASS, in addition differential delays due to GLONASS frequency must be applied. At the time of preparation of this paper we did not meet all these conditions. Although IGEX GLONASS precise ephemerides were available we did not yet finish the calibration trip of GLONASS receivers and could not determine GLONASS frequency differential delays between receivers involved in our test. In these conditions a test of intercontinental GLONASS P-code time transfer over about 6000 km between the BIPM and the United States Naval Observatory (USNO) was performed using modeled ionospheric delay and GLONASS broadcast ephemerides (see Figure 8).

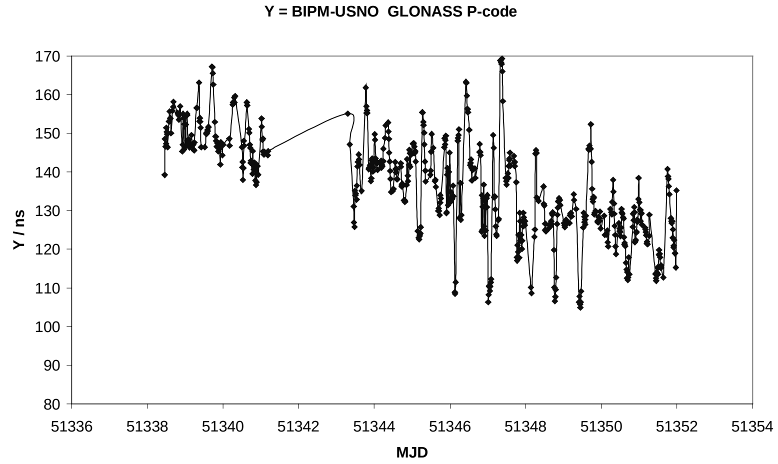


Figure 8. [*BIPM clock – UTC(USNO)*] compared by GLONASS P-code common view with broadcast ephemerides, modeled ionosphere delay, and without calibration GLONASS frequency biases.

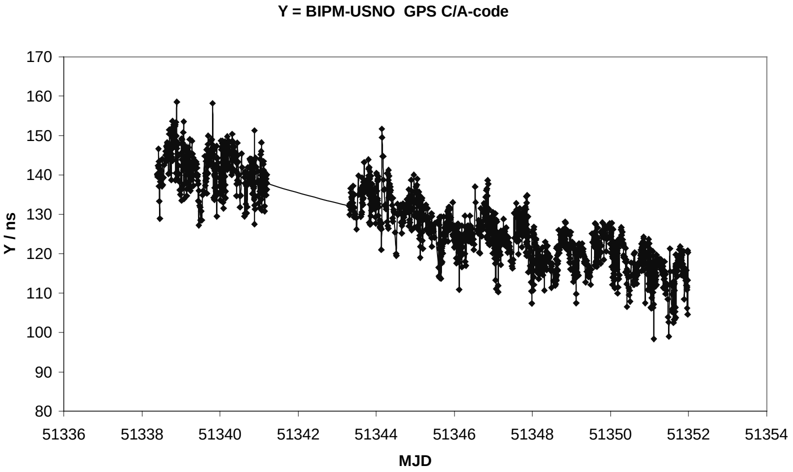


Figure 9. [*BIPM clock – UTC(USNO)*] compared by GPS C/A-code common view with broadcast ephemerides and modeled ionosphere delay.

The raw data have an rms deviation of about 6 ns when appropriately smoothed. This is slightly worse than a GPS C/A-code time transfer performed under the same conditions with modeled ionospheric delay and broadcast ephemerides (see Figure 9). This is due partially to the broadcast GLONASS ephemerides having a larger uncertainty than their GPS counterparts and partially to the GLONASS receivers frequency biases.

Conclusions

- The chip-length of GLONASS P-code is 5 times shorter than the chip-length of GPS C/A-code and 10 times shorter than the chip-length of GLONASS C/A-code. As a consequence the GLONASS P-code pseudo-range measurements are considerably more precise than comparable GPS or GLONASS C/A-code measurements.

- This has been effectively observed in the present study for one-site and short-baseline comparisons. GLONASS P-code single-channel data obtained in the course of a one-site comparison show noise reduction by a factor of 5 relative to GPS C/A-code single-channel data performance. The use of GLONASS P-code in multi-channel mode promises a gain in stability by a factor of about 3. Consequently for short baselines, the expected time stability for an averaging time of one day should be about 100 picoseconds, which corresponds to a frequency stability of 1 part in 10^{15}.

- The GLONASS P-code long-distance time transfer is showing similar performance to GPS C/A-code time transfer when performed in similar conditions using broadcast ephemerides and modeled ionospheric delay.

- Shortly after the IGEX Workshop in Nashville all conditions were met to apply to our long-distance test the IGEX GLONASS precise ephemerides. The results obtained are similar to the GPS time transfer performed with IGS precise ephemerides. These very first results will be further elaborated and published in a special issue of Journal of Geodesy dedicated to the IGEX-98.

Acknowledgments

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Computation of GLONASS Precise Ephemerides for International Time Transfer

Andrzej Drozyner
University of Olsztyn, Faculty of Geodesy, Licznerskiego 4
10-957, Olsztyn, Poland

Introduction

Precise orbits for the GLONASS satellite system have been computed within the framework of the IGEX (International GLONASS Experiment) campaign, using the TOP-GLONASS orbital system. Only the phase and code data from dual-frequency receivers were used. For high precision international time transfer highly precise GLONASS satellite orbits are required. Therefore this paper presents the mathematical model used for the calculations of the GLONASS satellite orbits, the clock model parameters and same additional parameters interesting in the IGEX campaign.

One of the main objectives of this paper is the application of the precise ephemerides to the long-distance common view time transfer using GLONASS satellites. For this reason, orbits are computed for the middle of satellite standard common-view tracks, to avoid interpolation.

The application of precise orbits in place of the broadcast ones, as well as the use of a precise ionospheric model, or ionospheric measurements, should result in a reduction of the uncertainty of intercontinental clock comparisons to the one nanosecond level.

TOP-GLONASS Software Package

The orbit computations were performed using the TOP-GLONASS software package developed at the University of Olsztyn / Institute of Geodesy and partly at the Nicholas Copernicus University in Torun / Institute of Astronomy. The TOP-GLONASS software package is the special segment destineted for GLONASS / GPS type of observations, which belongs to the TOP-DC (Differential Correction) - most general - differential correction program (Drozyner, 1995). To obtain high quality orbits of GLONASS satellites, which are essential for international time transfer, the force model for GLONASS satellites must be precisely defined.

Force Model for GLONASS Satellites and Estimated Parameters

The equations of motion for the GLONASS satellites, in the TOP-GLONASS orbital program, take into consideration:

- Geopotential: IGM-3 (16x16)
- Third body perturbation: point mass Sun and Moon
- Solid Earth tide
- Ocean tide

- Solar radiation pressure and albedo
- Unmodeled accelerations:
  - semi-major axis “rate” ($\dot{a}$)
  - radial, transverse (or tangential) and normal components.

Most of the above mentioned force model parameters are assumed to be known. If the GLONASS observations coming from the global network of the stations are processed, a few of parameters - listed below - are estimated:

- six cartesian or keplerian parameters
- two scaling factors for solar radiation pressure / orbital arc
- station clock error parameters (for orbital arc or for passes)
- space vehicle clock error parameters
- unmodeled effect parameters (semi-major axes “rate” and / or unmodeled empirical accelerations).

Observations, Their Reductions and Numerical Results

The transmission carrier frequencies chosen for the GLONASS satellites lie in the L-band. The observation types accepted by the TOP-GLONASS software package are:

- L1 pseudorange
- L2 pseudorange
- pseudorange combinations: difference, ionospheric-free,...
- L1 phase cycles
- L2 phase cycles
- phase pseudorange combinations: difference, ionospheric-free,...

Before comparison of observations with the mathematical model of satellite motion, the following reductions are applied:

- space vehicle antenna phase centre
- ionospheric refraction (Klobuchar model)
- tropospheric refraction (Lanyi or Saastamoinen or Hopfield model)
- relativistic delay due to beam bending in the Earth’s gravity field (at the moment not important).

As a numerical example, the week number 1013 was considered. Only pseudorange observations for the space vehicle in slot number 1 were processed. The corresponding RMS of fits is listed in Table 1.

Table 1. Residual RMS for Week Number 1013
SV slot number =1. Pseudoranges.

Station	RMS (cm)
BORG	31
GODZ	64
BRUG	40
HERP	65
KROG	45
MTKA	61
OSOG	59
STRR	55
THU2	65
USNX	51
VSLD	33
ZIMZ	66

For further investigations the double-differenced phase measurements will be used.

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