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Using GLONASS in Combined GNSS Receivers: Current Status

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BIOGRAPHY

Alexei E. Zinoviev received his MS in geodetic astronomy from Moscow Institute of Engineers for Geodesy, Aerial Surveying and Cartography (now – Moscow State University of Geodesy and Cartography). He joined Institute for Space Device Engineering (ISDE) in 1988, Ashtech Inc. in 1993 and Javad Positioning Systems in 1997. At present, he is with Topcon Positioning Systems as the leader of the Firmware Development team.

ABSTRACT

The paper focuses on using GLONASS in state-of-the-art combined GNSS (GPS/GLONASS) receivers in the light of the GPS and GLONASS current status. The launch of GLONASS-M satellite is an important event that opens new horizons for satellite navigation. Correspondingly, the description of advantages associated with new hardware and new navigation data of GLONASS-M satellites is given. Also, current status of GLONASS and plans of its modernization are considered. For combined use of GPS and GLONASS, interoperability issues that originate from differences in initial designing of both systems need to be resolved. It is demonstrated that such issues have been resolved at the level that meets all the practical needs. Also, there were interoperability issues connected with working in differential DGPS/RTK modes when RTCM messages served for broadcast DGPS/RTK data. It is shown that an appropriate solution has been found for each of those issues, thus the current version of RTCM standard is free of any GPS/GLONASS interoperability issues. Also, the materials on using GNSS receivers in different positioning modes are provided. Additional GLONASS satellites help in maintaining reliable RTK positioning under environments with limited visibility of satellites. At the same time, there are advantages associated with fast ambiguity resolution, detection and exclusion of anomalies etc. Also, questions related to precise GLONASS ephemerides and Network RTK applications are considered. Finally, a summary of advantages of GNSS receivers (that will support Galileo as well) over GPS-only receivers is given.

INTRODUCTION

GLONASS has achieved its Full Operational Capability (FOC) in January 1996 when 24 GLONASS satellites were available for positioning and timing. Unfortunately, since that time, due to GLONASS budget cuts and other problems that related to Russian economy in general, GLONASS constellation has dropped to seven satellites (November 2001). Four launches (“Proton” booster carries three GLONASS Space Vehicles (SVs) per one launch) of GLONASS took place on time span December 2001 - present. They have increased the total number of working SVs to 13 (July 2005). The important event was, also, the launch of the first GLONASS-M satellite that belongs to the new (second) generation of GLONASS satellites. After completing on-orbit tests, this satellite was marked “healthy” on December 9, 2004, and is now broadcasting new civil L2 signal as well as additional GLONASS-M navigation data that have to improve performances of GLONASS greatly.

Therefore, at present, there are 14 (taking into account one of GLONASS-M SVs that will have to be put into operation in autumn 2005) satellites that can be used along with GPS in geodesy and navigation. The total number of GPS+GLONASS satellites becomes 1.5 times greater than the total number of GPS-only satellites. It would be too prodigally to ignore these extra satellites, especially in the environment where receivers may face difficulties with tracking visible satellites (urban environment or a canopy area, for example). From the very beginning, Topcon Positioning Systems’ (TPS) receivers have supported tracking all the navigation signals, including GLONASS ones. However, combined processing of GPS plus GLONASS observables requires much more efforts in terms of algorithms and software. It is not mechanical extension of existing GPS processing methods to include additional satellites. There are GPS-GLONASS interoperability issues that need to be resolved to make corresponding algorithms working. The literature that deals with this subject has history that counts about fifteen years. In view of the fact that GLONASS is on the way to its revival (18 SVs will have to be orbiting by 2008), those issues, again, become actual, and they are worth re-examining.

Another side of GPS-GLONASS interoperability is connected with using of GLONASS in differential modes when a base sends GPS/GLONASS data to the rover receiver. The base may broadcast its data to the receivers of different manufacturers. In order to make such data usable, appropriate public standards need to be developed that would allow the receiver to identify and use differential data accordingly. The standards developed by RTCM SC-104 (Radio Technical Commission for Maritime Services, Special Committee 104) have gained the most common acceptance not only in maritime applications. Current version 3.0 [RTCM 3.0, 2004] contains many improvements that enable unambiguous and effective using of both GPS and GLONASS in RTK mode. Also, there are some clarifications related to previous version 2.3 [RTCM 2.3, 2001]. Corresponding questions are considered in the chapter related to RTCM GLONASS messages.

Many of previous publications included the discussions of advantages of GLONASS in the era when Selective Availability (SA) was available in GPS. Because of the absence of intentional degradation of performances, GLONASS played an important role in autonomous (stand-alone) positioning mode and in differential modes, if the base station sent data at slow rate or data link outages happened. Now the accents should be changed in favor of RTK mode, for which additional GLONASS satellites provide more reliable and continuous results, for example, at periods of time when the total number of GPS satellites may not be enough for positioning. Also, as GLONASS-M program is progressing and new satellites are put into operation, the importance of GLONASS for autonomous navigation will grow rapidly. Based on recent changes in the status of GPS and GLONASS, a revised review of using GLONASS in different positioning modes is given in the corresponding chapter.

GLONASS: PRESENT AND FUTURE STATUS

The launch of the first GLONASS-M satellites opens new prospects for satellite navigation. Mainly, this chapter focuses on the advancements associated with new GLONASS-M satellites (changes in the satellite hardware and new navigation signal/data). A review of current space and ground segments of GLONASS is also given. Future plans are considered too.

GLONASS space and ground segments

Currently (July, 2005), GLONASS constellation contains twelve GLONASS SVs and two GLONASS-M SVs (Table 1). One of GLONASS-M SV (GLONASS number 712) is undergoing tests. It is planned to put it into operation in autumn 2005.

Table 1. GLONASS constellation (July 2005).

GLONASS SV number	Plane/ Slot	Freq. chan.	Intro date (dd.mm.yyyy)	SV type
796	1/01	02	06.02.2005	GLN
794	1/02	01	02.02.2004	GLN
789	1/03	12	04.01.2002	GLN
795	1/04	06	30.01.2004	GLN
711	1/05	02	15.04.2003	GLN
701	1/06	01	09.12.2004	GLN-M
712	1/07	04		GLN-M
797	1/08	06	06.02.2005	GLN
787	3/17	05	04.11.2000	GLN
783	3/18	10	05.01.2001	GLN
792	3/21	05	31.01.2003	GLN
791	3/22	10	21.01.2003	GLN
793	3/23	11	31.01.2003	GLN
788	3/24	03	21.11.2000	GLN

The last column in Table 1 includes information about SV type: “GLN” depicts “GLONASS” type, “GLN-M” – “GLONASS-M” type. It should be noted that GLONASS number 711 (Slot 5) is a modification of “GLONASS” type. In comparison with “usual” GLONASS SV, Slot 5 has an extended lifetime (5 years vs. 3 years).

As it follows from Table 1, plane 1 contains all slots completed (eight in total), plane 2 has no available SVs and plane 3 contains six satellites. It is clear that the current GLONASS constellation does not provide autonomous navigation “24/7”, although four SVs at least are visible the most part of the day (at times, up to seven GLONASS SVs can be tracked). However, being used along with GPS, GLONASS satellites can be considered as a very useful GPS augmentation.

GLONASS ground segment, at present, consists of four TT&C stations: Komsomolsk-upon-Amur (Russia’s Far East), Yeniseysk (Siberia), Schelkovo (Moscow region) and St. Petersburg. There are also reserve stations, which are distributed along the territory of the Russia. Central synchronizer (atomic clocks) that maintains GLONASS system time is located at Schelkovo. GLONASS System Control Center coordinates activities related to orbit determination, computing time-frequency parameters, SV’s uploads etc. (Krasnoznamensk, Moscow region) [Revnivykh, 2005].

GLONASS-M satellites

GLONASS-M satellites belong to the second generation of GLONASS SVs. It is planned that eight GLONASS-M satellites have to be launched before the moment when the third generation GLONASS-K SVs become available. In comparison with its predecessor GLONASS, GLONASS-M has got serious advantages:

- extended guaranteed life-time (7 vs. 3 years);

- civil L2 signal;
- more stable clock ($1 \cdot 10^{-13}$ vs. $5 \cdot 10^{-13}$) and more accurate determination of SV clock corrections (8 ns vs. 20 ns);
- additional GLONASS-M navigation data;
- inter-satellite radio link;
- improved solar panel pointing (2 vs. 5 degrees);
- lower level of unpredicted accelerations;

Special attention was attracted to minimizing unpredicted accelerations. Corresponding changes in the satellite design should allow for reducing such accelerations to the level of $5 \cdot 10^{-10}$ m/sec². It has to improve dynamic models of the satellite motion. In total, mentioned above improvements have to increase the accuracy of GLONASS-M navigation signals in 2-2.5 times [Bartenev et al., 2005].

Important advantage of GLONASS-M is the ability to broadcast civil L2 signal that can be treated as an analog of L2C GPS signal. The structure of the new signal is the same as the structure of GLONASS C/A L1 signal. Unlike GPS, GLONASS does not encrypt its P-code signals, thus, today civil receivers can use GLONASS P-code “free of charge”. However, the encryption of P-code may be activated in the not so distant future. In this case civil L2 signal becomes of great importance for the civil GLONASS users community. Experiments related to tracking of civil L2 signal have already been carried out. Reliable and continuous tracking of GLONASS L2 civil signal has been demonstrated in Topcon Positioning Systems’ receivers.

GLONASS-M navigation data

GLONASS-M satellites broadcast new navigation data that occupy former spare bits of GLONASS subframes. New data include the following highlights:

- improved interoperability with GPS (word τ_{GPS}): now GLONASS-M satellites transmit time offset between GPS and GLONASS system times;
- improved on-board integrity checking (word I_n): GLONASS-M satellite reports about a problem not later than in 10 seconds after its detection;
- information about future leap seconds is available (word KP). (Such information can be received, also, from GPS navigation data);
- availability of absolute time (words N_T and N_4): current year, month and date can be derived from these words. Without these words, it was possible to get only modulo 4 years time in GLONASS-only receivers (current GPS data allow for about 20 years ambiguity);
- estimate of pseudorange accuracy is provided (word F_T): it allows the receiver to weight code observables in a more efficient manner. This

- parameter can be considered as an analog of URA (User Range Accuracy) word in GPS;
- hardware delay between L2 and L1 bands is given (word $\Delta\tau_n$): it improves evaluation of the state of ionosphere (GPS analog is the word τ_{GD});
- availability of UT1 time scale (words B1, B2): these words allow one to compute the difference $\Delta UT1 = UT1 - UTC(SU)$;
- resolution of the parameter τ_c (time offset between GLONASS system time and UTC(SU)) has been increased to 2^{-31} seconds.
- availability of the satellite slot number (word n);

All the listed above new navigation data have already been broadcast by GLONASS-M satellite (GLONASS SV number 701). These new navigation data have to greatly improve GLONASS overall performances. For example, the availability of the satellite slot number means that now receivers may not use GLONASS almanac for determining the correspondence between slot number and channel frequency number. In some cases it allows reducing the time of so-called “cold start” as well as simplifies the algorithms of the receiver firmware.

Also, the important feature of GLONASS-M navigation data is that GLONASS ICD guarantees that no navigation data uploads will occur on the interval of applicability of the word t_b (time to which ephemerides and clock corrections are referenced). It is especially important for differential modes (e.g. DGPS and RTK modes) when messages that include corrections with respect to broadcast ephemerides are in use. More details on this subject are given in the paragraph that includes materials on identification of GLONASS ephemeris data.

Modernization of GLONASS

GLONASS is on the way to its revival. In accordance with the Federal GLONASS Program that covers time period 2002-2011, minimal operation capability is expected to reach 18 GLONASS SVs by 2008. It is planned that the launches of the third generation GLONASS-K satellites will be started in 2007/2008. Along with the extended lifetime of 10 years, GLONASS-K will be capable of broadcasting L3 civil signal, on which integrity information for safety-of-life applications is available. The Russian government considers GLONASS as a high-priority program. Therefore, at present, GLONASS has enough funding and, hence, all the plans, which are connected with GLONASS modernization, have a good chance to be realized.

COMBINED USE OF GPS AND GLONASS

GPS and GLONASS were designed in the 70th for military purposes. At that time it was difficult to imagine that these navigation systems would ever be interoperable

with each other. Therefore, questions connected with combined use of GPS and GLONASS were not taken into account in the original design of both systems. The development and deployment of the systems went in parallel. In the beginning of 90th, it had become clear that GPS+GLONASS receiver might provide advantages over a solo (GPS-only or GLONASS-only) receiver provided interoperability issues will be resolved. Corresponding investigations were started. At present, one can conclude that all of those issues have been resolved at sufficient for practical needs level.

The most important issues are the followings:

- determination of transformation parameters for converting from PZ-90 to WGS-84 datum;
- computing the time offset between GPS and GLONASS system times;
- leap seconds in GLONASS;
- hardware biases between GPS and GLONASS channels;

Transformation from PZ-90 to WGS-84

GLONASS broadcasts ephemerides expressed in PZ-90 (*Parametry Zemli 1990 – Parameters of the Earth 1990*) datum while GPS uses ephemerides referenced to WGS-84 datum (which is the same as ITRF at decimeter level of accuracy). Definitions of coordinate frames of WGS-84 and PZ-90 are close to each other [GLONASS ICD, 2002; Parameters of PZ-90, 1998; WGS84, 1997]. Nevertheless, the realizations of WGS-84 and PZ-90 may use their own set of stations with defined coordinates, thus the difference between WGS-84 and PZ-90 coordinates may very likely take place. Thus, in order to compute coordinates when using GPS and GLONASS SVs, seven transformation parameters for converting from PZ-90 to WGS-84 datum (three translations, three rotations and scale) have to be known.

Further complication is connected with the fact that “original” PZ-90 (KGS (*Kosmicheskaya Geodezicheskaya Set’ – Space Geodetic Network*)), which is realized by means of a consistent set of 33 stations (26 points at the territory of the former Soviet Union and 7 points in Antarctica), and PZ-90 (GLONASS) that serves for broadcasting GLONASS ephemerides, are, in general, two different datum. There is a shift around Z-axis on the order of about 0.20 arc seconds between PZ-90 (KGS) and PZ-90 (GLONASS) (Table 2). It looks like such a shift originates from the process of implementation of PZ-90 (KGS) into the software of GLONASS ground complex.

When using combined GPS+GLONASS constellation, it is required to know the transformation between PZ-90 (GLONASS) and WGS-84 datum. There were many publications dealt with determination of the 7-parameter

Helmert transformation. They differ by methods used as well as the location of sites (global or regional). Ideally, the sites with defined WGS-84 and PZ-90 coordinates should be distributed worldwide for computing the most reliable set of the parameters. However, the sites with known PZ-90 (GLONASS) coordinates are not available out of the territory of Russia. Also, WGS-84 coordinates of such sites may not be determined. Thus, one has to use geodetic quality receivers in order to obtain PZ-90 (GLONASS) coordinates on WGS-84 sites or WGS-84 coordinates on PZ-90 (GLONASS) sites. These data serve as an input for the coordinate method of parameter determination. Another method assumes using the satellite ephemerides for computing transformation parameters. The orbits of GLONASS SVs, which are expressed in WGS-84 datum, can be determined from either observables recorded with GLONASS receivers or by means of using SLR, radar or optical measurements. Transformation parameters can then be derived from comparing such computed SVs’ WGS-84 coordinates with broadcast GLONASS ephemerides. It is the ephemeris method.

Table 2. Transformation parameters for converting from PZ-90 to WGS-84 datum.

ΔX [m]	ΔY [m]	ΔZ [m]	R_x [a. sec]	R_y [a. sec]	R_z [a. sec]	σ ($\times 10^{-6}$)
PZ-90 (KGS)						
Parameters of the Earth 1990 (1998). [Combined method (Russia)]						
0	0	1.0	0	0	-0.206	0
Bazlov Y.A. et al. (1999). [Coordinate method (Russia)]						
-1.1	-0.3	-0.9	0	0	-0.169	-0.12
Zubinsky V.I. (2000). [Coordinate method (Russia)]						
-1.08	-0.09	-0.41	0	0	-0.154	-0.14
PZ-90 (GLONASS)						
Misra P. et al. (1996) [Ephemeris method (Global)]						
0	2.5	0	0	0	-0.392	0
Roßbach U. et al. (1996) [Coordinate method (Europe)]						
0	0	0	0	0	-0.330	0
Mitrikas V.V. et al. (1998) [Ephemeris method (Global)]						
-0.47	-0.51	-2.00	-0.002	-0.001	-0.356	0.022
IGEX-98, BKG (1999) [Ephemeris method (Global)]						
0.06	0.07	-0.57	0.035	-0.021	-0.358	-0.01
IGEX-98 BKG/ESA (2000), 1040-1058 (GPS weeks) Zinoviev A.E. [Ephemeris method (Global)]						
0.00	-0.18	-0.36	0.010	0.007	-0.343	0.016
IGEX-98 (2000), Ostach O.M. [Ephemeris method (Global)]						
-0.03	-0.18	-0.49	0.009	-0.003	-0.358	0.014
Roßbach U. (2001) [Direct estimation method (Global)]						
0.40	0.36	-0.48	0.024	-0.012	-0.343	0
Boucher C., Z.Altamimi (2001) [Ephemeris method (Global)]						
0.07	0.00	-0.77	0.019	0.004	-0.353	-0.003

Table 2 contains the list of some sets of transformation parameters, which were computed during last years. Among them, the results, which are obtained at the interval 1999-2001, seem to be the most reliable ones because they are based on IGEX data that cover considerable time spans. As it follows from Table 2, the rotation around Z-axis appears to be the most important parameter. Effects related to other parameters are much smaller.

Given sets of parameters allow one to state that transformation parameters between PZ-90 (GLONASS) and WGS-84 datum are known with good enough accuracy for practical needs. Strictly speaking, the transformation parameters may vary with time [Mitrikas et al., 1998] (it can be also seen from analyzing IGEX data), thus they should be referenced to an epoch. However, the influence of such variation on SV coordinates will not be great. For example, assume the rotation around Z-axis may vary in the range of approximately -0.358 – 0.343 arc seconds. It corresponds to the variation on the order of ~ 1.85 meters in coordinates of GLONASS SVs. This error is equivalent to the error connected with broadcast GPS/GLONASS ephemerides (~ 2.0 meters for GPS, ~ 5 meters for GLONASS). Thus, when working in differential modes at short baselines, such an error will not affect performances. At long baselines, the uncertainty related to inaccurate knowing of transformation parameters will not be the main limitative factor in view of errors associated with broadcast ephemerides. Applications that require highest accuracy, for example, a network RTK software, can reduce such an uncertainty further because it is possible to compute the most appropriate set of transformation parameters suitable for given location (network). This optimum set of parameters can then be broadcast from the base to the rover receiver via a standard message.

It is difficult to select the best set of parameters among ones listed in Table 2. Analysis of GLONASS residuals based on experimental data, which were collected at a single point (Moscow) in July-August 2005 at moments when at least four GLONASS SVs were available for positioning, confirms that all the listed in the Table 2 transformation parameters that include Z-rotation in the range -0.358 – 0.343 arc seconds provide similar to each other results. Further experiments may provide arguments in favor of one of those sets of transformation parameters. From point of view of everyday needs, any set of the considered parameters provides good enough results.

Offset between GPS and GLONASS system times

Both GPS and GLONASS SVs broadcast (via navigation data) offsets between time scale of every satellite and corresponding system time. Also, information about the

offset between GPS/GLONASS system time and UTC (UTC(USNO) for GPS, UTC(SU) for GLONASS) is included in satellite subframes. In order to work with combined constellation, the difference between GPS and GLONASS system times needs to be known as well.

Usually, in autonomous mode, the offset between system times is included in the solution vector along with three components of receiver coordinates and receiver clock offset. It leads to the requirement to have five GPS+GLONASS SVs at minimum for computing a solution. In principal, such a requirement does not cause any problems until there is enough satellites in view. Nevertheless, if there are difficulties with tracking all available SVs (at obstructed locations, for example), the cost of each additional satellite may be high. Also, the offset between GPS and GLONASS system times changes slowly (Fig.1), thus it can be considered to be constant over short enough time intervals or it can be predicted. The use of such pre-determined offset has to improve performances of combined GNSS receiver provided the offset is known with good enough accuracy.

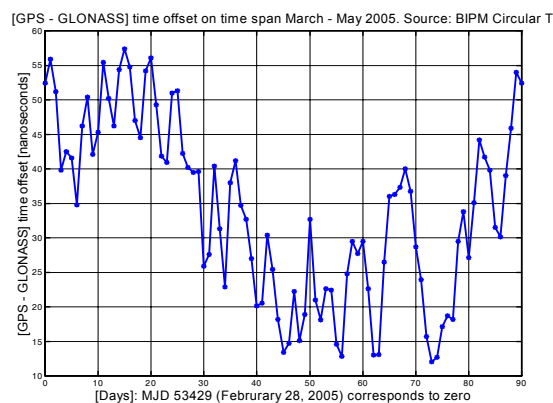


Fig.1 [GPS–GLONASS] time offset derived from BIPM Circular T (207-209) data.

As it was already noted, new GLONASS-M navigation data contain the offset between GPS and GLONASS system times. This offset can be obtained, also, from BIPM Circular T data [Circular T, 2005]. Fig.1 displays the offsets derived from Circular T data on time span March-May 2005. It needs to be taken into account that dispersion of individual measurements, which have contributed to determination of the offset, is less than about 20 ns while global uncertainty is on the order of hundreds of nanoseconds [Circular T, 2005]. Therefore, an offset may exist between “real” [GPS–GLONASS] offset and Circular T data. Also, these data are not available in real-time mode. Thus, other opportunities have to be exploited for getting “external” value of the offset.

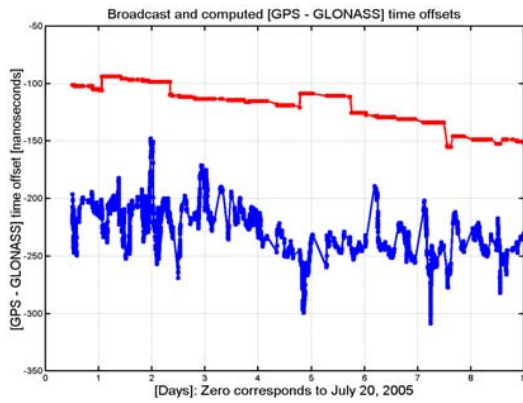


Fig.2 Broadcast (red) and computed (blue) [GPS–GLONASS] time offset.

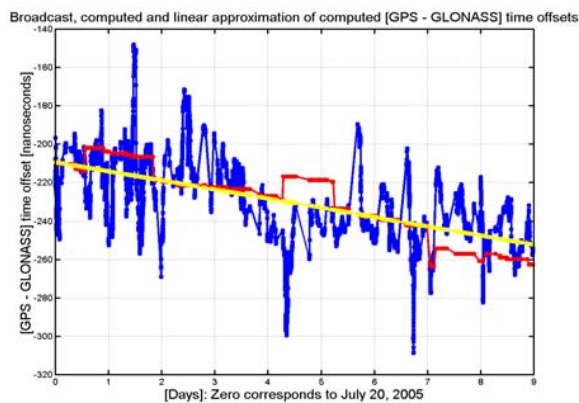


Fig.3 Referenced to the same origin broadcast (red), computed (blue) and linear approximation of computed (yellow) [GPS–GLONASS] time offset.

Broadcast (by GLONASS-M) [GPS–GLONASS] offset was recorded on time interval July 20–30, 2005 at Moscow. In parallel, on epochs when, at least, four GLONASS SVs were visible, Euro-GGD board computed this offset. Fig.2 contains two graphs that represent these offsets. The computed offset is noisy because the GDOP, associated with limited number of GLONASS SVs, was not optimum at some epochs. It can be seen that there is a constant offset between two graphs that equals about 100 nanoseconds. Obviously, in order to get rid of such an offset, some kind of calibration of the delay between GPS and GLONASS channels needs to be carried out. Fig.3 depicts the same data sets with the constant offset removed. Also, computed offsets are fitted by linear approximation. As it follows from Fig.3, graphs that depict broadcast and linear fitted offsets are in good correspondence with each other (on the order of 20 nanoseconds at maximum), thus the broadcast offset can be used for improving the accuracy of stand-alone or DGPS positioning provided the constant offset has been removed (or estimated). Further experiments are required for evaluation of applicability of broadcast [GPS–

GLONASS] offset in autonomous positioning mode. Initial results are very promising though.

Even if there is no source of “external” knowledge about [GPS–GLONASS] offset, the receiver itself can determine its averaged value by means of some kind of filtering and extrapolate obtained values at next epochs in order to get advantages over “snapshot” solution. In the opposite case (i.e. when “external” offset is available), the receiver can estimate the constant “delta” between broadcast and computed offsets in order to use this “delta” on next epochs even after power off/on. Summing up, in autonomous mode of positioning the existence of [GPS–GLONASS] time offset does not lead to any significant problems in GNSS receivers, especially in view of availability of the broadcast offset.

Leap seconds in GLONASS

In contrast to GPS, GLONASS system time is connected to UTC, thus GLONASS receivers have to include the appropriate logic in order to work at the moment of leap second addition properly. Current GLONASS ICD [GLONASS ICD, 2002] includes recommendations that describe logic for correct work of GLONASS receiver at such moments. In fact, an appropriate logic was already tested in GNSS receiver (JPS’ Euro-168 board) on December 31, 1998 when the most recent leap second was added to UTC.

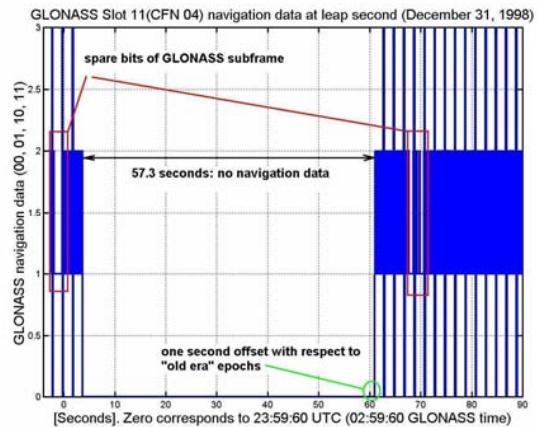


Fig.4 GLONASS Slot 11 (FCN 04) navigation data, which were recorded near the moment of leap second addition (December 31, 1998).

To maintain GLONASS signals tracking at the moment of leap second addition, the receiver firmware was modified accordingly. Another goal was to provide full use of GLONASS SVs for positioning. Additionally, for further analysis, GLONASS navigation data were recorded over the interval that included leap second. These navigation data are shown in Fig.4 that depicts four states of 20 milliseconds long data bit as a function of time for GLONASS SV Slot 11 (channel frequency number 4).

Navigation data themselves can take only two states: 01 and 10; preamble includes 00 and 11 states as well. Therefore, it is easy to see the borders of each string of GLONASS subframe that occupies two seconds (1.7 seconds of navigation data and 0.3 seconds of preamble). Also, one can see spare bits in GLONASS navigation data that correspond to the subframe that includes almanac data for four satellites (before leap second) and spare bits extracted from the fourth and fifth strings of the subframe (after leap second).

In Fig.4, zero corresponds to the moment 23^h59^m60^s UTC. It can be seen that just after leap second addition, the satellite continued to transmit first two strings of the subframe, which were referenced to “old” UTC (on interval 1.7 seconds long). However, the preamble of the second string was not broadcast: the satellite began to transmit navigation data filled with zeroes. Then, in 57.3 seconds, the satellite started to broadcast navigation data referenced to “new” UTC (note one second offset with respect to 60th second). Accordingly, ephemeris data were also referenced to current UTC.

From the point of view of GNSS receiver normal operation, no problems were found: all GLONASS SVs (three in total) were tracked without any interruption. Also, all of those satellites participated in computing the position that did not demonstrate any jumps in coordinates. Therefore, leap seconds in GLONASS do not degrade performances of GNSS receivers provided a corresponding logic has been implemented in the receiver firmware.

Hardware biases

GPS and GLONASS require different hardware for tracking their L1 and L2 signals. Consequently, hardware biases for RF parts may exist in GPS and GLONASS channels of the same receiver. Also, because of FDMA, in which each satellite transmits on a different frequency, biases between GLONASS channels may exist as well. All those biases that may change with time because of, for example, temperature, need to be taken into consideration – especially in RTK mode. It is worth noting, also, that the use of the same type equipment in differential mode may almost completely remove such biases.

When working in RTK mode, GPS receivers constantly estimate the following biases: $[GPS_{L1}-GPS_{L2}]$, $[GPS_{L1}-GLN_{L1}]$ and $[GPS_{L1}-GLN_{L2}]$ (some details, which are partly outdated, can be found in [Rapoport et al., 1999]). It is also important to minimize these biases at pre-release stage to make computation of those biases more robust. For achieving this goal, the receivers include hard-coded corrections, which are determined in the process of calibrating the given type receivers. Another resource that allows reducing the hardware biases is a proper choice of

hardware components. All the mentioned methods lead to significant removal of hardware biases in GNSS receivers.

GLONASS MESSAGES INTEROPERABILITY IN CONTEXT OF RTCM STANDARDS

GNSS standards, which are developed by RTCM SC-104, play a role of de-facto standards not only in maritime applications but also in many other high-precision applications (such as surveying, for example). It is important to provide compatibility between GNSS receivers of different manufacturers when working in differential modes. There were some issues that affected interoperability of RTCM GLONASS messages in previous versions (2.2 and 2.3) of the standard. That’s why the status of GLONASS messages was set to “tentative” as opposed to “fixed” status of GPS messages [RTCM 2.3, 2001]. Fortunately, it is not the case for the most recent version 3.0 [RTCM 3.0, 2004], which is free of any unresolved issues related to GLONASS messages (currently, GPS/GLONASS messages, which are intended for RTK mode, are defined in the text of the standard). The discussion of the issues that might affect GLONASS messages interoperability in the past is in the text below.

GLONASS messages interoperability issues

Standard transformation from PZ-90 to WGS-84 datum. When base station sends GPS/GLONASS corrections to the rover receiver, it is required to know transformation parameters between PZ-90 and WGS-84 datum, which were used for computing these corrections. Such a requirement originates from the statement that GPS/GLONASS corrections have to be referenced to coordinates expressed in WGS-84 and PZ-90 datum respectively. The difficult choice of the most appropriate parameters among the listed, for example, in Table 2 can be avoided because in differential modes the errors associated with inaccurate knowing of the parameters will be effectively removed (especially on short baselines). On the basis of the results described in [Zinoviev, 2001], the version 2.3 defines standard transformation parameters for computing GPS/GLONASS corrections: rotation around Z-axis is equal to -0.343 arc seconds, all other parameters are set to zero [RTCM 2.3, 2001]. This set of the parameters provides good enough results in differential modes.

The correspondence between GLONASS slot number and channel frequency number (CFN). GLONASS messages, which are defined in the versions 2.2 and 2.3, use satellite slot number as a satellite ID. However, RTK engine needs to know CFN for processing carrier phase observables. It means that rover receivers have to have GLONASS almanac for converting slot number into CFN. In order to get rid of such dependence, RTCM 3.0 GLONASS

messages contain both slot number and CFN. In all possible cases, such an approach allows the rover receivers to process RTK data immediately upon their reception.

Relativistic correction. RTCM versions 2.2 and 2.3 state that relativistic correction has to be taken into account when computing GLONASS corrections. In fact, the relativistic correction has already been added to the word $\gamma_n(t_b)$, thus no additional corrections are required.

GPS and GLONASS messages synchronization. There is a time offset between GPS and GLONASS system times that may change with time (due to leap seconds). From the other side, combined GNSS receiver has to obtain GPS and GLONASS messages, which are referenced to the same epoch. Also, in order to reduce latency of computed solution when working with the base that transmits GPS-only data, GNSS receiver has to “understand” that no GLONASS data will follow GPS messages (or vice versa). All the mentioned problems are resolved by means of using of “Multiple Message Indicator”. It is a bit that contains “1” if more data, which are referenced to the given epoch, follow. Therefore, receivers do not need to wait for next epoch data in order to identify the end of data for the current epoch.

Also, other two important issues are connected with identification of GLONASS ephemeris data and proper choice of the step of numerical integration.

Identification of GLONASS ephemeris data

The problem originates from the fact that GLONASS ephemeris data may change without a corresponding change in the word t_b , sometimes more than once (so-called “Issue Of Data (IOD) problem”). At the same time, GPS/GLONASS messages that include corrections computed with respect to satellite orbits have to contain an ID of ephemeris data to allow using the same ephemeris data at the rover receiver side. In GPS, parameters IODE and IODC play a role of such an ID. GLONASS does not contain a separate word that could serve for this task. Correspondingly, the description of the procedure, which is intended for recognizing GLONASS ephemeris data, exploits the words t_b and t_k in the versions 2.2 and 2.3 respectively. However, such a description in the version 2.3 seems to be too complex to be appropriate in practice. Also, the given procedure does not seem to provide a reliable identification of GLONASS ephemerides.

To overcome the above mentioned problem, so-called “IOV (Interval Of Validity) approach” was developed. Its description can be found in [RTCM-270, 2002] as well as in current RTCM documents. The idea is simple: the base broadcasts information that includes time tag of one of the

previous GLONASS subframes and the total number of subframes having the same ephemeris data. It defines time interval, over which no change of ephemeris data took place. Provided one of the subframes from this time interval at least has been received at the rover receiver side, DGPS/RTK corrections can be properly used. Therefore, IOV approach provides the reliable and straightforward identification of GLONASS ephemeris data.

It was already noted in the text above that in accordance with current GLONASS ICD, GLONASS-M satellites do not inherit IOD problem from GLONASS SVs, thus the word t_b , in principle, can be used as an ephemeris ID. Nevertheless, it needs to be confirmed by experimental data whether or not such an intention will be fulfilled in reality. Anyway, IOV approach serves for both “old” and “new” satellites equally well. Thus, there is a solution for GLONASS IOD problem that fully meets all the requirements.

Step of numerical integration

Unlike GPS, GLONASS does not use close analytical formulae for computing SV position. Instead, GLONASS uses a state vector referenced to given epoch (t_b). For computing SV coordinates/velocity at the moment t , one needs to use numerical integration (4th order Runge-Kutta method as defined in [GLONASS ICD, 2002]) over time interval ($t-t_b$). ICD does not define the value of the step of numerical integration though. Consequently, different results may be obtained if different steps of numerical integration are used. This issue is important for GLONASS RTK messages that include “corrections” (Message Type 20 and 21) because the accuracy of computing the SV coordinates has to correspond to LSB of the bit fields that contain observables. Such LSB equals 1/256 cycle (about 0.00073 for GLONASS L1) and 0.0005 meters for versions 2.3 and 3.0 respectively (at present, version 3.0 does not support any messages that work in terms of “corrections”; however, such messages may be added to next versions). Accordingly, for RTK messages, the errors of computed SV positions must not exceed 0.00037 and 0.00025 meters. For DGPS (code differential) messages, much greater error is acceptable (on the order of a few centimeters).

It appears that some kind of standardization needs to be performed to make sure that both the base and the rover receiver use steps of numerical integration, which would not affect the accuracy of the corrections. For evaluation of the error associated with the size of the step of numerical integration, 2213 GLONASS ephemeris data sets (different from each other) were collected over time interval July 20-30, 2005. The errors of numerical integration were estimated at points, which were ± 20 minutes distant from ephemeris reference time (t_b). Such a

choice was made in order to provide 5 minutes overlap of adjacent ephemeris data because the base may delay the broadcast of the corrections, which are computed with respect to the most recent ephemeris, to allow the rover receiver to collect the same ephemeris data. Three methods of numerical integration were tested: classic 4th order Runge-Kutta, 5th order Fehlberg and 7th order Shanks. The coordinates, which were computed by means of using of five seconds step, served as a reference.

Table 3. Errors of methods of numerical integration vs. step size (2213 ephemeris data, July 10-20, 2005).

Step of numerical integration [seconds]	Errors (maximum/RMS) inherent to methods of numerical integration [meters]		
	Runge-Kutta (4 th order)	Fehlberg (5 th order)	Shanks (7 th order)
5	0.000000	0.000000	0.000000
	0.000000	0.000000	0.000000
30	0.000056	0.000000	0.000000
	0.000043	0.000000	0.000000
50	0.000436	0.000001	0.000000
	0.000330	0.000000	0.000000
60	0.000904	0.000001	0.000000
	0.000685	0.000001	0.000000
90	0.004466	0.000010	0.000000
	0.003381	0.000008	0.000000
120	0.014464	0.000041	0.000001
	0.010950	0.000036	0.000001
150	0.035305	0.000126	0.000003
	0.026729	0.000110	0.000002
180	0.067394	0.000286	0.000006
	0.051033	0.000250	0.000006
210	0.123188	0.000609	0.000014
	0.093290	0.000532	0.000012
.....			
420	1.870151	0.018279	0.000458
	1.416796	0.016000	0.000378

Table 3 contains maximum and RMS errors, which were estimated for those three methods. It can be seen that when using Runge-Kutta 4th order method, 50 seconds step provides a good trade-off between effectiveness and maximum permissible error. Two other methods are much more accurate: maximum allowed steps are equal to approximately 180 and 420 seconds for Fehlberg and Shanks methods respectively.

Therefore, RTCM standards have to contain wordings related to maximum step of numerical integration allowed. For Runge-Kutta 4th order method, which is “prescribed” by GLONASS ICD, maximum step should not exceed 50 seconds when computing RTK corrections. This step can be significantly increased if more accurate method is in use. Actually, the only important requirement is to keep the relative error of SV ephemerides computed at the base and the rover receiver

below a specified limit. Absolute error of integration may reach a few decimeters without any degradation of performances on short baselines. Thus, it is also possible to define a “standard” step of integration (180 seconds, for example) and use smaller values at the last step of integration only. In that way, the base and the rover receivers will always follow the same steps for computing SV positions, thus the resulting relative error will be less than the allowed one.

USING GLONASS IN DIFFERENT POSITIONING MODES

It is obvious that being used solely, current GLONASS constellation of 14 SVs is too insufficient for providing continuous autonomous navigation. However, GLONASS can play an important role of GPS augmentation that improves performances of GPS-only receivers – mainly, when working in differential modes. To some extent, such GLONASS SVs can be considered as additional GPS satellites. It is the conception known as GPS+ in Topcon Positioning Systems’ receivers (e.g., HiPer[®] family of GNSS receivers). Advantages of such an approach and details related to the use of GLONASS in different modes of positioning are given below.

Autonomous navigation and real-time differential positioning modes

After turning off Selective Availability in GPS in May 2000, the use of GLONASS does not bring any significant improvements to position accuracy in autonomous (stand-alone) positioning mode. Nevertheless, GLONASS can be still useful for providing better redundancy in the environment where satellite visibility may be limited. Also, RAIM (Receiver Autonomous Integrity Monitoring) benefits from using a greater number of satellites. The word F_T , which is being broadcast by GLONASS-M satellite, has to improve combined use of GPS and GLONASS for autonomous navigation because this word (along with the word URA in GPS) contains an estimation of accuracy associated with code measurements of given satellite, thus the scheme of weights can be tuned thoroughly. Another resource that may improve performances in autonomous mode is the use of fixed [GPS–GLONASS] time offset as discussed earlier. In view of more accurate positioning, which is provided by GLONASS-M SVs, as well as in view of improved integrity monitoring (word I_n), the importance of GLONASS for autonomous navigation should grow rapidly, if GLONASS modernization goes as planned.

For applications that require high-precision positioning (such as geodesy and surveying), main advantages of GLONASS become apparent when working in differential modes. The rover receiver that works in DGPS or RTK modes benefits from using additional GLONASS

satellites dramatically. There is no big difference in performances under open sky. However, in the environments where SVs visibility is limited (urban or canopy areas, sites located near trees or buildings etc.), each additional satellite may be of great importance. Also, for a period of time up to tens of minutes, gaps may occur in current GPS constellation (July 2005), during which total number of GPS satellites may not be enough for reliable RTK positioning at the given location. Even with current constellation of 14 SVs, additional GLONASS SVs allow GNSS receivers to work under many environments where GPS-only receivers fail. Yet another advantage, which is provided with additional satellites, is connected with using Co-Op tracking [Zhodzishsky et al., 1998]: high elevation satellites, including GLONASS, may help in tracking GPS/GLONASS satellites having lower elevations. It improves the quality of observables.

When comparing real-time performances of geodetic quality receivers, the parameters related to the ability to get “fixed” RTK solution are of the main interest. There are numerous publications that discuss ambiguity resolution in view of availability of GLONASS SVs. The results of comparative evaluation of various RTK systems, one of which was capable of tracking GLONASS, can be found in [Radzeviciute et al., 2003]: the performances of GPS+GLONASS system were the best in terms of mean initialization time. It coincides with the results described in [Landau and Vollath, 1995]: GLONASS increases the speed of fixing of GPS ambiguities. The very fast (often instant) OTF ambiguity resolution can be achieved when using low cost single frequency GPS+GLONASS receivers on short baselines [Kozlov and Tkachenko, 1997].

Usually, combined GPS+GLONASS fixed RTK solution is computed. However, it is possible, also, to get GPS-only or GLONASS-only fixed RTK solutions, provided enough number of satellites is in view. At long baselines (a few tens of kilometers), the getting of combined GPS/GLONASS RTK solution may become a more difficult task because of less accurate broadcast GLONASS ephemerides.

The important part of GPS/GLONASS processing in RTK mode is filters that provide detection and exclusion of anomalies that may exist in satellite signals. It is connected with more fundamental task of detection and exclusion of any anomalies that may occur in radio-navigation field, satellite navigation data or receiver firmware/hardware. Such filters help in providing reliable and continuous RTK positioning. The anomalies may happen in both GPS and GLONASS, despite the fact that original five GPS monitoring stations provide (almost) worldwide coverage while GLONASS stations are located at the territory of Russia only. Anomalies in GLONASS happen more often in comparison with GPS. However,

such anomalies, which, as a rule, can be effectively filtered out, are definitely quite a rare event that does not affect everyday RTK performances.

During last years, the use of Network RTK software has become an essential part of many applications. Like the rover receiver that uses single base, the rover receiver in Network RTK mode, also, benefits from using additional GLONASS SVs that serve for maintaining more robust RTK positioning when working with VRS or FKP data. Standardization of Network RTK messages is currently underway within RTCM SC-104. RTCM Network RTK messages, which are based on the approach described in [Euler et al., 2001], have to support both GPS and GLONASS Network RTK corrections. The approach, which is given in [Rapoport et al., 2002], uses constraints that originate from simultaneous processing of GNSS RTK data, which are received from up to three bases, at the rover receiver side. It significantly improves RTK performances in comparing with single base RTK. Such an approach can be especially useful for a local region where installing quite expensive Network RTK software may not be optimal solution.

Precise GLONASS ephemerides

GLONASS can be effectively used, also, in post-processing mode: the use of a greater number of SVs may reduce time, which is required for collecting static data. Availability of precise ephemerides allows for getting more accurate results, especially at long baselines. At present, there are over 50 stations that comprise the GLONASS tracking network within the IGS. Four Analysis Centers support the computing of GLONASS precise ephemerides: BKG, CODE, ESA and MCC [Slater et al., 2004]. At CODE (Center for Orbit Determination in Europe at the University of Berne), a rigorous GPS/GLONASS combined analysis is performing. As a result, the accuracy of Final GLONASS orbits, which is confirmed by orbit validation using SLR tracking data, equals about 5 centimeters (RMS) [Schaer, 2005]. Such accuracy is more than enough for post-processing mode. Also, Rapid and Ultra-rapid GLONASS products are available at CODE.

Advantages of GNSS receivers

It would be useful to sum up advantages of state-of-the-art combined GPS/GLONASS (GNSS) receivers in the light of current GPS and GLONASS status. All of those advantages are, in fact, the consequence of increased redundancy, which is provided by combined use of GPS and GLONASS:

- ability to work under environments with limited visibility of satellites;
- fast OTF ambiguity resolution;

- GNSS receivers remove periods of time when total number of current GPS satellites may not be enough for reliable positioning at given location;
- more robust detection and exclusion of anomalies;
- improved quality of observables when Co-Op tracking is in use;
- improved estimation of tropospheric and ionospheric parameters;
- time, which is required for collecting static data, can be reduced;

It should be noted, also, that the use of GLONASS can provide additional advantages when working in high latitudes (Alaska, Canada, Scandinavia etc.) because of higher inclination of GLONASS orbits in comparison with GPS ones (64.8 vs. 55 degrees). Due to the work at different frequencies, GLONASS is also more resistant to interference and jamming.

Future European Galileo system, which is being developed, has to provide further advantages. Galileo is in more advantageous position with respect to GPS and GLONASS in the sense that many issues related to interoperability with existing navigation systems have been taken into consideration in initial design of Galileo. Future GPS/GLONASS/Galileo receivers have to become a standard for high-precision positioning.

CONCLUSIONS

1. The launch of new GLONASS-M satellites opens new horizons for satellite navigation.
2. All the interoperability issues that might affect combined use of GPS and GLONASS in different positioning modes have been resolved at sufficient for practical needs level.
3. GLONASS is a reliable system that provides superior performances of GNSS receivers, especially in RTK mode under environments with limited visibility of satellites (urban or canopy areas, sites located near trees, buildings etc.).

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