Progress in transferring time using GLONASS satellites

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ABSTRACT

The Soviet Union's global navigation satellite system, GLONASS, currently has nine pre-operational satellites with the full complement of twenty-four satellites available possibly in two years at the present launch rate. Since only a single satellite is required for time transfer to a known location, the potential of Glonass as a disseminator of time and frequency can be evaluated in this pre-operational phase.

This paper discusses the timing references available from Glonass and how they are employed in a satellite-to-user time transfer link. Using the Glonass low precision codes, and without making dual frequency corrections, time transfer with Glonass is obtainable to precisions of the order of 100 nanoseconds or better. Data is presented showing the relationship between Glonass system time and UTC(USNO) over an extended period of time. Finally the linking of Glonass system time to UTC(SU) is shown to have been established since late 1988.

INTRODUCTION

Glonass provides worldwide time dissemination and time transfer services in the same manner as the NAVSTAR GPS and exhibits the same advantages as Navstar does over other existing timing services [1]. Time transfer is both efficient and economic in the sense that direct clock comparisons can be achieved via Glonass between widely separated sites without the use of portable clocks. Event time tagging can be achieved with the minimum of effort and users can reacquire Glonass time at any instant due to the continuous nature of time aboard the satellites.

The first release from the Soviet Union of detailed Glonass information occurred at the International Civil Aviation Organisation (ICAO) special committee meeting on Future Air Navigation Systems (FANS) in Montreal in May 1988 [2]. The report contained nominal orbital information as well as detailed descriptions of the Glonass C/A code structure and transmitted data message. Most of this information had already been made available via other publications [3], [4], [5]. The reader's attention is directed to the references at the end of this paper for more general Glonass information. Currently nine Glonass satellites are in full operation giving single satellite coverage at most locations almost 24 hours a day. These satellites are listed in Table 1 (Glonass 38 is included in the Table although its health gives cause for concern).

SAT ID	COSMOS	GLONASS	CHN	L1/MHz
1988-43A	1946	34	12	1608.7500
1988-43B	1947	35	23	1614.9375
1988-43C	1948	36	24	1615.5000
1988-85A	1970	37	18	1612.1250
1988-85B	1971	38	7*	1605.9375
1988-85C	1972	39	10	1607.6250
1989- 1A	1987	40	9	1607.0625
1989- 1B	1988	41	6	1605.3750
1989-39A	2022	42	16	1607.0625
1989-39B	2023	43	17	1605.3750

* health marginal
Current Active Glonass Satellites 1-11-89.
Table 1

TIME FROM GLONASS

Time transfer from Glonass is achieved in a straightforward manner, Figure 1. Each satellite transmits signals referenced to its own on board clock. The Control Segment monitors the satellite clocks and determines their offsets from the common Glonass system time. The clock offsets are then up loaded to the satellites as part of the transmit data message. A user at a known location receives signals from the satellite and by decoding the data stream modulated on to the transmission is able to obtain the position of the satellite, as well as the satellite's clock offset from the common system time, as a function of time. Hence the signal propagation time can be calculated at any instant. The time at which the signals are transmitted is also contained in the data message; by combining this with the propagation time and correcting for the satellite clock offset, the user can effect transfer to Glonass system time. Any other user who has a satellite visible is also able to transfer to the same time scale.

Though this simplistic approach will provide time transfer to the Glonass system time additional errors occur which must be corrected for or an allowance made for them in the error budget.

1) Position errors. Both the transmitted satellite ephemeris and the user's known location can contain errors which appear as biases in the measurements. This is particularly relevant in the case of Glonass as the co-ordinate system reference frame which is used is at present unknown and thus it would prove more profitable to solve for user position as well as time offset to remove position uncertainties.

2) Atmospheric delays. The transit time of the signals are affected by delays in the troposphere and ionosphere. Tropospheric delay can be minimised by selecting satellites at high elevation angles and can also be accurately modelled. The ionospheric delay is usually the largest error in time transfer. Models also exist for this, such as that used by the Navstar GPS, but are generally less accurate. The Navstar model results in a rms reduction in range error of 60 percent [6]. Ionospheric effects can be removed most effectively by making dual frequency measurements.

3) Errors may result in the calculation of signal propagation time if proper account is not taken of delays due to the rotation of the earth during the signal propagation time. This is a function of satellite position and user latitude. For the worst case of a user at the equator and a satellite due east or west on the horizon this effect can result in an error of

approximately 128 nanoseconds in the case of Glonass. The earth rotation error can be easily calculated and removed.

4) Receiver noise and biases. Receiver noise with zero mean can be removed by simple averaging, which can be readily applied for a stationary user. Biases such as receiver delay can also be subtracted from the measurements.

5) Other errors exist such as imprecision in satellite clock correction parameters and affects such as multipath.

SIGNAL TIMING REFERENCES

Timing references are contained in both the satellite code and transmitted data. The Glonass C/A code is a 511 bit maximal length sequence transmitted at a rate of 511 Kbits/s giving a code epoch every millisecond. The Glonass data message is represented as 50 baud data modulated on to the satellite code. The data transitions are co-incident with code epochs. The data is transmitted as 2.5 minute superframes; each superframe is divided into 5 half-minute frames and each frame consists of 15 two-second lines of data. Each frame contains the current time, satellite ephemeris, clock correction parameters and almanacs for five other satellites. Hence five frames are required to obtain all the almanacs. The 1 second epochs occur in the data at the beginning (even second) and middle (odd second) of each line. Figure 2 shows the content of one data frame.

GLONASS DATA MESSAGE

SATELLITE EPHEMERIS

Glonass ephemerides are represented by satellite ECEF position and velocity vectors as well as acceleration correction components. In general the ephemerides are updated half hourly giving a maximum ephemeris extrapolation period of 15 minutes. To calculate the satellite position the equations of motion of the satellite can be numerically integrated over the prediction period.

$$\ddot{\underline{r}} = -\frac{\mu}{r^3}\underline{r} + \nabla\left[\frac{3}{2}J_2\mu\frac{R_\oplus^2}{r^3}\left(\frac{1}{3} - \frac{z^2}{r^2}\right)\right] \tag{1}$$

Equation (1) gives the equation of motion of the satellite with a correction for the second zonal harmonic (J_2) of the earth's oblateness which is by far the largest perturbation on the Glonass satellites over the ephemeris validity period. Translation of position and velocity from the ECEF frame to the inertial frame is necessary before integration. The equation of motion can be expressed [7] in constituent components by equations (2) to (4).

$$\ddot{x} = -\frac{\mu}{r^3}x - \frac{3J_2\mu R_\oplus^2 x}{2r^5}\left(1 - \frac{5z^2}{r^2}\right) \tag{2}$$

$$\ddot{y} = -\frac{\mu}{r^3}y - \frac{3J_2\mu R_\oplus^2 y}{2r^5}\left(1 - \frac{5z^2}{r^2}\right) \tag{3}$$

$$\ddot{z} = -\frac{\mu}{r^3}z - \frac{3J_2\mu R_\oplus^2 z}{2r^5}\left(3 - \frac{5z^2}{r^2}\right) \tag{4}$$

These equations can be integrated by any suitable technique (Runge-Kutta 4th order for example) and with a suitable step size the satellite's position can be easily calculated to within 3 metres over half an hour. The acceleration terms in the data message correct for additional perturbations to the satellite's motion which are predominantly luni-solar in origin.

SATELLITE CLOCK OFFSETS

The satellite clock offset from the common Glonass system time is represented by two parameters [2].

1) γ_n - the relative frequency offset between the nth. satellite navigation signal frequency, f_n, and the nominal value, f_{hn}, of the nth. satellite frequency.

$$\gamma_n = \frac{f_n - f_{hn}}{f_{hn}} \tag{5}$$

2) τ_n - the nth. satellite time scale shift relative to the Glonass time scale.

The Glonass system time, t_{sys}, is related to the satellite time, t_{sv}, by,

$$t_{sys} = t_{sv} + \tau_n - \gamma_n(t - t_o) \tag{6}$$

$$\dot{\tau}_n = -\gamma_n \tag{7}$$

where t_o is the time of validity of τ_n and γ_n. In addition a third parameter τ_c representing the difference between Glonass system time and Moscow Time is transmitted.

Table 2 shows the range and resolution of the Glonass clock correction parameters.

Glonass	Bits*	Scale	Range	Resolution	Units
τ_n	22	2^{-30}	$\pm2\times10^{-3}$	9×10^{-10}	s
γ_n	11	2^{-40}	$\pm9\times10^{-10}$	9×10^{-13}	s/s
τ_c	28	2^{-27}	±1	7×10^{-9}	s

* *MSB = sign bit.*

Glonass clock correction parameters.

Table 2

GLONASS TIME TRANSFER MEASUREMENTS

A series of measurements have been conducted of the difference between UTC(USNO) and Glonass system time. The arrangement of equipment to carry out these measurements is shown in Figure 3. A prototype single channel Glonass/Navstar GPS receiver has been constructed [8] which allows time comparisons between Glonass or Navstar system time and a 1 pps reference synchronised to UTC(USNO) available from a commercial Navstar receiver specified to be within 100 nsec of UTC(USNO) but in practice significantly better than this figure. The Navstar system time / UTC(USNO) comparison is used as a calibration and confidence measurement since the offset between GPS time and UTC(USNO) is known and transmitted as part of the GPS data message. The measurements are conducted as follows.

A time interval counter measures the interval between the UTC(USNO) 1 pps and millisecond epochs decoded from the code generator of the test receiver. Whilst tracking a satellite time interval measurements are thus made of UTC(USNO) against the clock of the satellite currently being tracked but also including the signal propagation time. This measurement is then related to UTC(USNO) against system time by the following equations.

$$\rho = \mathrm{UTC(USNO)} - t_{sv} + t_p \qquad (8)$$

where, ρ = counter reading.

t_{sv} = satellite time.

t_p = signal propagation time (modulus 1 ms)

$$t_{sv} = t_{sys} - \delta t \qquad (9)$$

where, t_{sys} = system time.

δt = difference in system time and satellite time.

$$\rho = UTC(USNO) - t_{sys} + \delta t + t_p \tag{10}$$

$$UTC(USNO) - t_{sys} = \rho - t_p - \delta t \tag{11}$$

The resolution on each measurement is 2 ns and the UTC(USNO) 1 pps is certainly accurate to within 100 ns. Measurements are made once per second, averaged over 3 minutes; the data is then stored for off-line processing.

DATE	SATELLITE	READINGS (1/SEC)	AVERAGE OFFSET/ns	STANDARD DEVIATION/ns
12/3/89	NAVSTAR 3	4320	-336	22
12/3/89	NAVSTAR 6	2520	-325	18
12/3/89	NAVSTAR 9	2340	-327	23
12/3/89	NAVSTAR 11	5580	-336	19
12/3/89	NAVSTAR 12	3420	-330	14
12/3/89	NAVSTAR 13	4990	-352	16
12/3/89	GLONASS 34	3960	29696	24
12/3/89	GLONASS 35	4860	29700	24
12/3/89	GLONASS 36	4320	29699	26
12/3/89	GLONASS 38	4320	29705	35
12/3/89	GLONASS 39	3780	29703	35
12/3/89	GLONASS 40	4140	29740	24
12/3/89	GLONASS 41	4680	29713	19

Navstar and Glonass system time offset from UTC(USNO).
Table 3.

Table 3 shows a set of measurements over a typical 24 hour period. The data has been corrected for tropospheric, relativistic and earth rotation effects but not for ionospheric effects. Since the measurements are taken over one day then the data is obtained from two passes of each satellite. An elevation mask of 10 degrees is used. The offset of UTC(USNO) from Navstar system time over this period as transmitted by the Navstar data message is about -344 ns demonstrating the effectiveness of the cross-calibration and lending confidence to the measurements of Glonass system time. The results relating Glonass system time to UTC(USNO) are very encouraging from the point of view of both consistency from one Glonass satellite to another (maximum difference in offset of the order of 50 nsecs) and of precision of the measurement (typically 20-30 nsecs). Since the largest unaccounted error (ionospheric propagation) is also of the order of 30 nsecs), the measurement limits have been reached.

GLONASS TIME SCALES & UTC(SU)

Figure 2 shows a plot of UTC(USNO) against Glonass system time over a period of about 12 months using an ensemble of available satellites. The plot shows clearly two phases of operation, the change-over occurring in March 1989. The first phase is characterised by a frequency offset of 0.18 ps/s and the second by an offset of 0.64 ps/s clearly indicating a frequency adjustment of the Glonass system time clock at the change-over point.

An additional clock correction parameter is included in the Glonass data message which relates the Glonass system time scale to the time scale at which ephemeris and satellite clock offsets are calculated. We will call this time scale Glonass ephemeris time; the offset between Glonass ephemeris time and Glonass system time is denoted in the transmitted data message by the parameter τ_c. Observations of τ_c over a period in excess of two years shows the offset between the time scales always maintained within approximately $\pm 30\mu s$ of each other. Under normal circumstances application of this parameter in the calculation of satellite location and clock offset is unnecessary since a nominal satellite velocity of 4 km/s and clock frequency offset of the order of 10 ps/s will provide insignificant corrections when changing from Glonass system time to ephemeris time. Figure 3 shows a plot of τ_c over the same time period as Figure 2. It can be seen that τ_c provides a somewhat less continuous time scale than Glonass system time. There is clear evidence of frequency changes in the plot and in addition a phase shift of about $3\mu s$ early in December 1988. The major significance of this phase change in seen in Figure 4 which portrays how the various Glonass time scales are linked. There are three separate traces on the plot which are as follows:-

1) Measurements at the University of Leeds of UTC(USNO) against Glonass system time as in Figure 2 but to a new time scale.

2) The same results as in 1) referred to Glonass ephemeris time by subtracting the transmitted parameter τ_c.

3) BIPM data giving UTC(USNO) - UTC(SU) as referred to the international reference centre in Paris for coordination of universal time (UTC).

Before early December 1988 Glonass ephemeris time was not identical with UTC(SU) but the phase reset at that time referred to earlier clearly initiated the synchronism of the two scales. This move was probably planned to take place by the start of 1989; during the whole of 1989 Glonass ephemeris time has been identical to UTC(SU). Reference of UTC(SU) to the BIPM by conventional means has been sporadic since July 1988. Clearly the time has arrived when international time coordination will be carried out primarily by means of navigation satellites, either those of the United States (Navstar GPS) or the

Soviet Union (Glonass). The implications for high-quality international time transfer as well as acccurate and precise position-fixing on a continuous, global basis are

CONCLUSIONS

It has been demonstrated that time transfer with Glonass to a static user can be achieved to accuracies of the order of 100 ns or better while using the Glonass low precision C/A code phase and without dual frequency measurements. Results are repeatable cross-calibration with Navstar GPS provides a high confidence level. Glonass system time provides a time scale which has reliability and performance comparable to that of other international time scales and can be used as an intermediate time scale for clock comparisons between widely separated sites.

A direct linking has now been confirmed between Glonass system time and UTC(SU) as of late 1988. Previously Glonass system time had been referred to Moscow Time which was clearly not the same as UTC(SU). Now that both Navstar GPS and Glonass are both referred to their respective national time standards, UTC(USNO) and UTC(SU) respectively, the prospects for international time transfer by satellite are very encouraging.

Allan variance stability profiles of satellite system time as measured against UTC(USNO) have been produced extending from 1 to 64 days indicating the use of high-quality atomic oscillators, either Cesium or more likely Hydrogen Maser clocks, as the fundamental reference for Glonass system time.

Clearly the time has arrived when international time coordination will be carried out primarily by means of navigation satellites, either those of the United States (Navstar GPS) or the Soviet Union (Glonass). The implications for high-quality international time transfer as well as acccurate and precise position-fixing on a continuous, global basis are extremely important.

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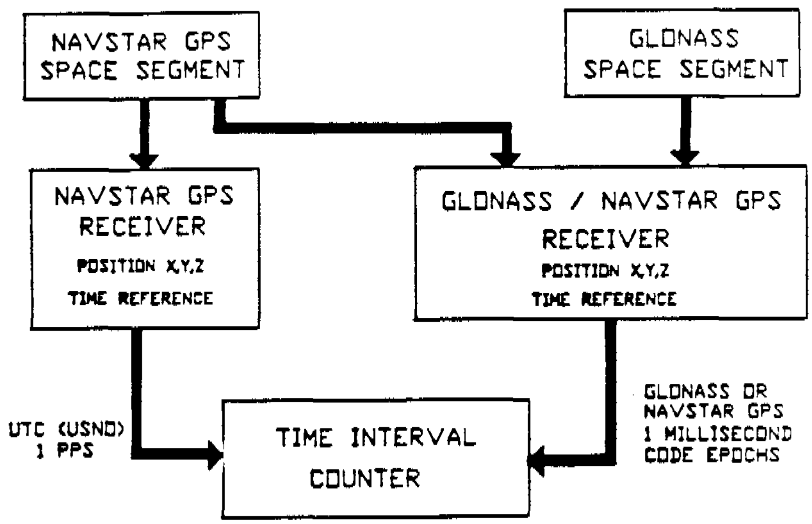

FIGURE 1.

TIME TRANSFER EQUIPMENT ARRANGEMENT

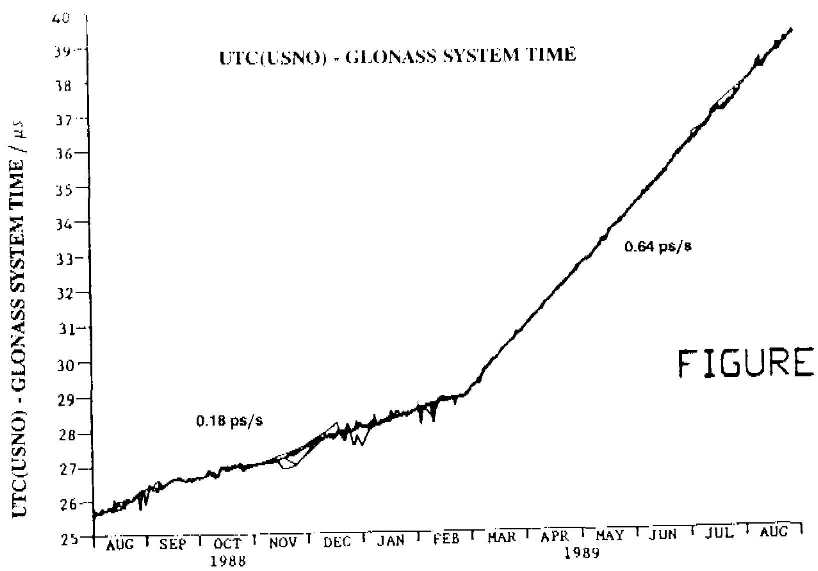

FIGURE 2.

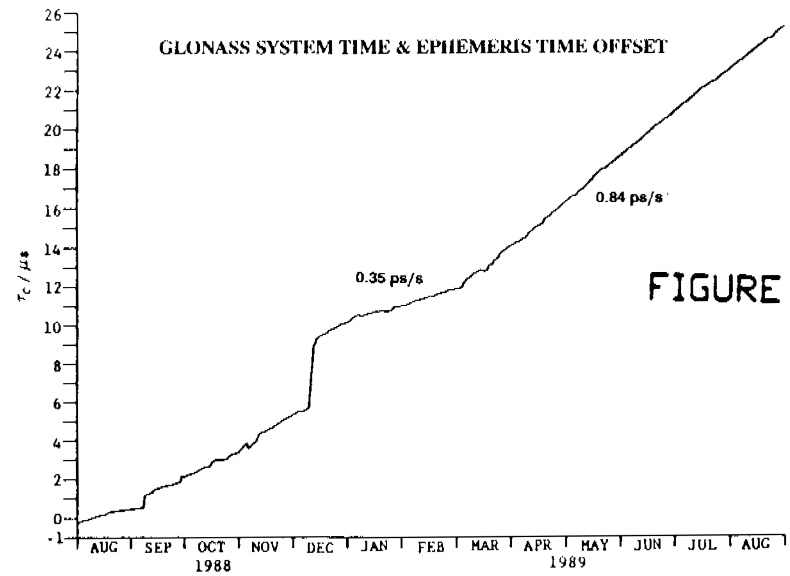

FIGURE 3.

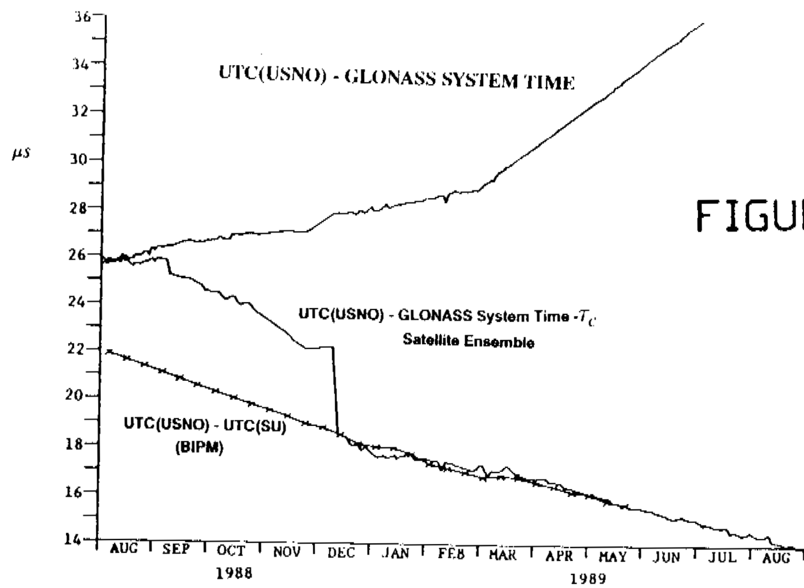

FIGURE 4.

QUESTIONS AND ANSWERS

ROBERT VESSOT, SAO: Can you tell me, in your opinion, what is the species of clock that they are most likely to have in orbit? I have heard reports of vastly improved rubidiums and ghastly cesiums, etc. What is your professional opinion?

MR. DALEY: Somebody put you up to that, right? I really don't want to say a lot about it, except that our evidence is that they are carrying atomic clocks. We have seen increasing performance of the on–board clocks. Evidence is that the present clocks are probably every bit a good as the NAVSTAR clocks. I say probably, because we have not finished our analyses yet. The early clocks were, as you say, representative of poor or mediocre rubidiums. Those steps in performance have been made over the last three years and I have no doubt that they will go on.

CARROLL ALLEY, U OF MARYLAND: Is there any evidence that the Soviet system itself is degraded, or is it working at its maximum performance?

MR. DALEY: We have no evidence of any degradation in performance, deliberate or otherwise. That doesn't say that it is not happening or couldn't happen. We look at the (edges ?) from GLONASS everyday, probably several hours a day, and we have never seen any evidence of SA or any other form of degradation. I believe that the Russians have announced that they can't do it even if they want to. Whether that is true or not, I don't know.

MR. VESSOT, SAO: Have you seen any evidence of cross–linking, satellite–to–satellite, in order not to wait for an orbit to send commands?

MR. DALEY: That one is easy—no, I don't know.

ROBERT VESSOT, SAO: What about corner reflectors? Do they have them? Professor Alley has, for at least a decade, been pleading with our people to put a corner reflector on one of these to resolve the clock *vs.* propagation and ephemeris issue. Do they have these?

MR. DALEY: My understanding is that some if not all of the GLONASS's do have corner reflectors on them.

MR. VESSOT: Can we track them then? We should be able to.

MR. DALEY: There are people in the audience who can answer that question much better than I can.

PROFESSOR ALLEY: Let me respond to that. Bob, there is an (name not clear) satellite which is totally covered with corner reflectors in the GLONASS orbits. It would be nice if there were corner reflectors on the GLONASS satellites themselves.

MR. DALEY: It is only hearsay, I have been told that they do.

PROFESSOR Alley: The half hour changes in the ephemeris message, is that transmitted from the ground to the satellites, or is it just a programmed change?

MR. DALEY: It is a programmed change.

PROFESSOR ALLEY: Do you have any idea how often they update the ephemeris?

MR. ALLEY: Almost certainly once a day.