

EFFICIENT METHODS FOR HIGH-PRECISION SYNCHRONIZATION OF SPATIALLY- DISTRIBUTED OSCILLATORS OF NON-REQUEST MEASURING STATIONS FOR GLONASS

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ABSTRACT

This paper considers basic methods for high-precision synchronization of spatially-distributed reference oscillators of non-request measuring stations for GLONASS without their delivery to the location of frequency and time reference. New solutions for tropospheric and ionospheric error estimation and reduction during synchronization are provided.

Key word: GLONASS, non-request measuring stations, hydrogen frequency reference, ionospheric error

GLONASS design involves creating, developing and maintaining the network of non-request measuring stations (NMS). The main functions of these stations are to define on-time signal frequency deviation of each navigational satellite and to transmit the data to control station in order to correct or in case of malfunction to eliminate it. If such solution is not timely taken, this can affect end users of navigational information, cause failures, emergencies etc.

However, accurate and appropriate estimation of satellite signal frequency is only possible with reliable operation of NMS receiving equipment and in particular its oscillators which generate reference frequencies. To estimate ephemeris – time parameters of satellite position NMS oscillators must be precisely synchronized with reference timescale. The remote position of NMS and non-serviced operation mode add complexity to this task.

Thus, the major purpose of the research is to synchronize precisely two remote oscillators (reference and NMS oscillators) in order to get experimental errors close to potential reproduction fidelity of NMS equipment reference timescale as well as to generate frequency at fixed - point operating with one satellite known coordinates of ≈ 5 ns and $\approx 4 \cdot 10^{-12}$ respectively.

One of the possible accomplishment is to equip NMS with high-stability reference oscillator (e.g. hydrogen-frequency standard Ch1-1006 or hydrogen maser Ch1-75), but in this case the unwanted oscillator drift can also result in inefficiency of NMS. In this way, it is necessary to perform periodical comparison of frequency standard with time – and – frequency standard similar to the one in SRIM (Siberian Research Institute of Metrology), Novosibirsk.

However, the delivery and frequency comparison of hydrogen standard from remote NMS at least once a year make GLONASS control system economically impractical.

In addition, the delivery of standard (or reference oscillator to NMS) can negatively affect the frequency comparison results due to strict temperature, mechanical disturbances and other requirements.

Further, we will consider tried and tested methods for high-precision synchronization of NMS remote hydrogen standard which require no delivery.

Remote synchronization is based on differential method of estimating the time interval (in seconds) changes applied to carrier phase (phase pseudorange) for a navigation satellite (NS) being simultaneously radiovisible at the frequency standard and NMS locations. It eliminates the impact of on-board frequency standard instability, but requires considering ionospheric and tropospheric errors, multipath effect, the measurement errors of time intervals and frequency standard instability in NMS.

To reduce the reference oscillator instability in NMS and at the same time to improve the system reliability we have proposed and tested the combination of two frequency standard acting as reference and control frequencies. When maser Ch1-

75 operates in a free-running mode without auto-tuning of a resonator to hydrogen spectral line frequency, the frequency instability is nearing $(5...8) \cdot 10^{-13}$. The use of two frequency standards in NMS allows to automatically tune the resonator of master maser to hydrogen spectral line frequency and thus to reduce its instability up to $(3...5) \cdot 10^{-14}$.

The measurement error of time intervals between the marks (for example, on consumer devices of MRK type), which reproduce the timeline in seconds of onboard navigation satellite frequency standard, and second mark frequency standards of SRIM (Siberian Research Institute of Metrology) or non-request measuring station NMS hours is 10 ... 30 ns (when time intervals measurement instrument Ch3- 64 is used for measuring errors). This will equal to the total error $(2,3...6,9) \cdot 10^{-14}$ for 12 hour intervals of synchronized satellite signal reception.

Equipment error in terms of delay involves constant and random components. The analog part calibration of user device radiopath, mounted on NMS, can eliminate the constant delay influence on synchronization error. Delay measurement error in radiopath during calibration is about few nanoseconds. Since equipment error is temperature dependent, along with constant component delay calibration there is a need in temperature compensation of its changes and equipment temperature control (at least of analog hardware components).

The methods of constant equipment error elimination are beyond the scope of this research as they require separate explanation and consideration. However, the application of MRK type equipment in NMS suggests that this error is essentially eliminated.

This paper focuses on the methods for ionospheric and tropospheric error reduction, ways of multipath mitigation as well as the reduction of random component of time and frequency measurement uncertainty in consumer equipment to get the values close to potential ones.

Due to the delay and ionospheric bending, the delay measurement error of signal propagation from NS depends on elevation angle, where the NS is observed,

and according to estimation available, can range from (10...30) ns at the elevation angles more than 30° to (30...150) ns with satellite reception close to the horizon.

The signal propagation delay error caused by tropospheric influence is (5...15) ns when operating with NS at elevation angles $\geq 30^\circ$ and (50...80) ns with navigation satellites close to the horizon.

The multipath error is caused by NS signal reflection from nearby objects at the receiving point. The reflected signals interfere direct signal at the antenna, distorting the radio navigation parameters estimation. For obvious geometrical reasons, the multipath error is mostly exhibited in relation to navigation satellites at low elevation angles. The multipath can add to the delay measurement error and consequently to synchronization error up to (10...30) ns.

The total effect of ionosphere, troposphere and multipath reception on the reference timescale error is ≈ 25 ns when operating with satellites at high elevation angles and ≈ 160 ns with satellites close to the horizon.

It should be noted that the error increase of synchronization relative to potential one will be less affected by the outlined factors in terms of frequency estimation than of time estimation. This owes to the fact that time estimation error is affected by absolute values of signal delay in ionosphere and troposphere, while frequency estimation error is affected by time rate of these delays i.e. the time rate of phase pseudorange (PR), which is so small that can be ignored in algorithms [4].

The ionospheric error reduction is traditionally gained by the use of ionospheric models as well as by simultaneous signal reception in two different frequency bands ($L1$ and $L2$ with frequency spacing ≈ 350 MHz).

The models allow to reduce the ionospheric error up to (50...75) %. Thus, time synchronization error can be reduced to (3...10) ns while operating with satellites at elevation angles of 30° and more.

The simultaneous signal reception in two frequency bands enables to reduce ionospheric error of PR estimation up to ≈ 1 m, which corresponds to ≈ 3 ns synchronization error contribution. However, the successful implementation of

dual-frequency method requires that signal $L1$ and $L2$ group delay in forming and radiating paths in navigation satellite should be equal to receiving and processing paths in user devices.

An alternative to dual – frequency method of ionospheric delay correction is the method of single – frequency correction based on incremental difference measurement of group and phase delay caused by ionospheric delay change with the change of satellite elevation angle [3]. This method involves no dual – phase signal reception and consequently equipment requirements but it will need signal reception during a certain period of time (approximately 10...15) min. in order to get ionospheric delay estimation.

The dual – phase user devices enables high – precision estimation of disagreement between code and phase PR (being a main source of errors), resulting from the change of satellite signal delay in ionosphere at the time interval t provided by incremental difference measurements of phase PR in the frequency range $L1$ and $L2$ at the same interval.

In fact, if the ionospheric delay change results in disagreement between code and phase PR in $L1$, so the corresponding disagreement will emerge in the $L2$. Cooperative processing of measurement result data (phase and code collaborative filtering) in $L1$ and $L2$ allows to obtain the information demanded.

Phase PR and their increments are measured with high accuracy (in millimeters). The typical dependence of mean square deviation of phase estimation error of carrier frequency signal phase from elevation angle of navigation satellite (GLONAS # 22) is shown in Figure 1.

Figure 1 illustrates that mean square deviation (MSD) of phase measurement varies in range from ≈ 1 mm to ≈ 7 mm. Consequently, MSD corrections to PR, which are calculated by phase measurement difference in $L1$ and $L2$, will approximately range from ≈ 5 mm to ≈ 30 mm for code PR $L1$ and from ≈ 7 mm to ≈ 50 mm for code PR $L2$.

Conducted field research of dual-frequency collaborative filtering based on MRK type user device showed that with the corrections calculated by difference of phase PR increments in L1 and L2 the difference between code and phase PR at the same frequency, for example, L1 does not sensibly change throughout the whole period of NS flight.

Figure 2 demonstrates the graph of code and phase PR difference variations in relation to maximum value with account for result corrections of code PR measurement in post processing. To maintain the experimental integrity, the measurement of code PR at real –time signal reception in user device was pursued without corrections of code and phase PR mismatch caused by ionospheric error variation. A common integrator with time constant $T \approx 30$ s. was used as a filter.

It is clearly seen that correction has significantly reduced the variation range of code and phase PR difference variation in relation to maximum value.

Elimination of ionospheric delay influence on phase PR increment enables to reach performance potential of frequency comparison phase methods of remote oscillators. The collaborative filtering of code and phase PR in MRK type user device is also used in order to reduce random component of code PR measurement error.

The collaborative filtering in code PR evaluation loop uses the information on PR increment on the sampling interval of measuring system obtained from carrier frequency tracking loop (phase PR increment).

This approach is based on the fact, that on relatively short time intervals (from few to several tens of seconds) the phase PR increment resulting from NS movement perfectly matches with code PR increment.

The use of collaborative code and phase filtering allows to reduce random (noise) component of code PR estimation error up to (0,05...0,2) m.

The influence of tropospheric component of error can also be reduced by using models. As input data the model (for example, Saastamoinen) uses NS

elevation angle value as well as meteorological data gathered nearby equipment location: temperature, relative humidity and atmospheric pressure. Residual error in this case does not exceed (1...2) ns.

Nowadays, the widespread acceptance is given to models of tropospheric correction applying not up-to-the minute meteorological data gathered by meteorological stations which form a part of NMS equipment, but statistic data accumulated for long time observation. The input data for such models are current date/ time along with NMS location data. In most cases such models have residual error of tropospheric delay about 3 ns.

The best known methods for multipath mitigation are:

- choke ring antennas which reject reflected signals from underlying surface and reflective objects below the antenna plane;
- phased array which can focus on a satellite, thus providing suppression of reflected beams from any other directions.

NMS can employ the following easy to implement approaches to reduce errors caused by multipath propagation due to signal reflection from nearby objects:

- installation of NMS antenna in places where the influence of reflected NS signals from nearby objects can be suppressed or reduced;
- rejection of navigation satellites with low elevation angle while performing the NMS oscillators synchronization.

However, the collaborative filtering in dual-phase consumer devices, used in NMS, permits to almost completely mitigate the multipath effect influence on the results of oscillators remote synchronization.

In fact, after the signal have been grabbed and joint delay tracking filter has turned into steady operation (with the correction of code and phase PR mismatch due to ionospheric delay variation), any observable mismatch of code and phase PR can be assessed as auxiliary error.

In particular, such mismatch can result from multipath effect which affects code and phase PR differently. For code PR the multipath signal reception error can be within meters, while for phase - within centimeters.

The set of code PR measurements, obtained over NS flight, which contains the multipath signal reception error and its comparison with Multipath Null Point (for example, when passing through zenith) makes it possible to develop a profile of multipath reception error depending on azimuth and NS elevation angle. This profile can be applied in real – time correction of code PR measurements while performing NMS oscillators remote synchronization.

Figure 3 shows the architecture of NMS installed in the Krasnoyarsk Research Centre of Siberian Branch of the Russian Academy of Sciences (KRC SB RAS) and used to test the suggested solution for remote synchronization. The testing procedure involved the synchronization of NMS hydrogen-frequency standards along with their comparison to secondary time and frequency standard in SRIM (Novosibirsk)

The NMS during the field testing included the following components:

- RM – receiving module of MRK equipment providing signal T_{NS} , which describes the position of moment of NS time scale.

- HS_1 and HS_2 – master and reference hydrogen frequency standards providing two types of signals – sequences of pulses per second which define time scale position of both T_1 and T_2 standards and standard frequencies F_1 and F_2 with value $F = 5$ MHz corresponding to these time scales;

- PC_1 and PC_2 – phase comparators which measure phase progressions ΔF_{12} and ΔF_{21} for further estimation of phase differences

$$\frac{\Delta F_{12}}{F} = \frac{F_1 - F_2}{F} \quad \text{and} \quad \frac{\Delta F_{21}}{F} = \frac{F_2 - F_1}{F}$$

- time-interval meter Ch3-64 with resolution ability of 1 ns operating with external reference frequency of 5 MHz and fed from HS_1 ;

- synchrometer Ch7-15 reproducing with microsecond precision the moments of measuring of time intervals t_i , where $i = 1, 2, \dots, n$;

– CM –commutator, which enables successive connection of time-interval meter Ch3-64 to channels metering the differences of moments of time scales $\Delta_1(t_i) = T_{\text{HC}}(t_i) - T_1(t_i)$, $\Delta_2(t_i) = T_{\text{HC}}(t_i) - T_2(t_i)$ and the differences of phase progressions $\Delta F_{12}(t_i)$, $\Delta F_{21}(t_i)$, where $i = 1, 2, \dots, n$.

– PC –personal computer, which control the commutator operation as well as store the results of Ch3-64 measurements and the moments of carrying out measurements t_i .

To operate the NMS auxiliary equipment for time and frequency synchronization of oscillators the software developed by SRIM was applied.

At time moments t_i the standard meter in SRIM measures the scale difference between navigation satellite T_{NS} and scale $UTC(H_M)$

$$\Delta_3(t_i) = T_{\text{NS}}(t_i) - UTC(H_M, t_i), \text{ where } i = 1, 2, \dots, n.$$

Assuming that measurements of time intervals $\Delta_1(t_i)$, $\Delta_2(t_i)$ in NMS (KRC SB RAS) and $\Delta_3(t_i)$ in SRIM are taking simultaneously from the same navigation satellite, the differences can be calculated through measurement results

$$\Delta_{13}(t_i) = \Delta_1(t_i) - \Delta_3(t_i) = UTC(H_M, t_i) - T_1(t_i),$$

$$\Delta_{23}(t_i) = \Delta_2(t_i) - \Delta_3(t_i) = UTC(H_M, t_i) - T_2(t_i)$$

between the moments of time scales of secondary standard meter in SRIM and the clock frequency standard in NMS KRC.

The obtained differences are used in estimation of NMS hydrogen standards– HS_1 и HS_2 deviation from nominal value.

$$\begin{aligned} \frac{\Delta F_1}{F} &= \frac{\Delta_{13}(t_{i+1}) - \Delta_{13}(t_i)}{t_{i+1} - t_i}, \\ \frac{\Delta F_2}{F} &= \frac{\Delta_{23}(t_{i+1}) - \Delta_{23}(t_i)}{t_{i+1} - t_i}. \end{aligned} \tag{1}$$

The obtained frequency estimation are verified through equating to the results of additional measurements $\Delta_{12}(t_i) = T_1(t_i) - T_2(t_i)$, $\Delta F_{12}(t_i)$ and

$\Delta F_{21}(t_i)$, which are further used to calculate frequency difference estimation between HS₁ и HS₂

$$\frac{\Delta F_1 - \Delta F_2}{F} = \frac{\Delta_{12}(t_{i+1}) - \Delta_{12}(t_i)}{t_{i+1} - t_i},$$

$$\frac{\Delta F_2 - \Delta F_1}{F} = \frac{\Delta\Phi_{21}(t_{i+1}) - \Delta\Phi_{21}(t_i)}{t_{i+1} - t_i}, \quad (2)$$

$$\frac{\Delta F_1 - \Delta F_2}{F} = \frac{\Delta\Phi_{12}(t_{i+1}) - \Delta\Phi_{12}(t_i)}{t_{i+1} - t_i}$$

The equation (1) with regard to (2) allows to reduce the level of random estimation errors taking place in metering channel paths.

Thus, we propose the following procedure of time-and-frequency synchronization of remote highly-stable NMS oscillators.

1. The timing of synchronous measurements of differences $\Delta_1(t_i)$, $\Delta_2(t_i)$ in NMS and $\Delta_3(t_i)$ in SRIM as well as the choice of navigation satellites for measurements are conducted in SRIM and is further sent by e-mail into NMS (in KRC SB RAS).

2. The measurements are arranged twice a day. Time between measurements is 12 hours.

3. Every measuring consists of 30 fixations of differences $\Delta_1(t_i)$, $\Delta_2(t_i)$, $\Delta_3(t_i)$ at one second interval. The average differences at the interval of 30 seconds are taken as measurement result. In this respect the time of first fixation t_i is taken is an average measurement result.

4. The measurement results for 5...8 measurings are sent by e-mail to SRIM, where the correction calculations for the moments of time scale $\hat{\Delta}_{13}(t_i)$, $\hat{\Delta}_{23}(t_i)$ and for the frequency estimations $\frac{\Delta\hat{F}_1}{F}$; $\frac{\Delta\hat{F}_2}{F}$ are performed. By the correction calculation the analytical corrections to operational time scale *UTC* are applied.

5. The calculated corrections $\hat{\Delta}_{13}(t_i), \hat{\Delta}_{23}(t_i)$ and $\frac{\Delta\hat{F}_1}{F}; \frac{\Delta\hat{F}_2}{F}$ are used as frequency corrections to HS₁ and HS₂ standards and serve to compensate the time scale offset of HS₁ reference standard in relation to system time scale.

It should be noted that this procedure allows to conduct remote synchronization with only one hydrogen frequency standard in NMS given the availability of error increase due to unpredictable and non compensated offset of NMS frequency standard scale (3...5 times).

If the frequency standard of another NMS being previously checked against the reference serves as one of the hydrogen standard, it enables remote synchronization of those oscillators of NMS which don't have radiovisibility of one and the same navigation satellite with the reference in SRIM. Thus, it makes possible the full remote synchronization of all NMS spatially distributed frequency standards with required periodicity without their dismantling, transportation and other time and cost consuming measures. This method also ensures no losses in NMS service capability and no service interruptions. The increase of time and number of measuring sessions leads to the reduction of above errors.

The key feature here is that the use of phase measurements carried out simultaneously in two NMS allows to estimate the phase difference of mounted reference oscillators with error $1 \cdot 10^{-14} \dots 1 \cdot 10^{-13}$ on the interval ≈ 100 seconds. However, additional NS signal phase increments due to ionospheric delay measurement did not allow to implement these potential capabilities, reducing the comparison accuracy on short time interval on $1 \cdot 10^{-11} \dots 1 \cdot 10^{-10}$.

However, on long intervals (in hours) the error can be $\approx 1 \cdot 10^{-12}$.

The paper introduces the methods of consideration, calibration and correction for different error components as well as the certain principles of NMS oscillator frequency comparison with the reference standard. These methods are aimed to provide the non-request measuring stations being developed for GLONASS with effective, high-precision and economically effective

synchronization of reference oscillators to secondary time and frequency standard with errors close to potential ones.