Time scales collation and transfer with sub-nanosecond accuracy using laser ranging and pseudoranging measurements

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Abstract. *The paper presents description and results of tests on collation of the time scales of four distributed SLR stations using a method for determination of difference between one-way and two-way laser ranges to a GLONASS satellite equipped with retroreflector system and laser pulse photodetector. It is shown that the tested equipment provides LTT (Laser Time Transfer) with the error of no more than 100 ps. The guidelines on how to increase LTT availability based on the use of a radio-laser network (GS-LTT) are suggested.*

During the tests we used a method based on comparing the measurement results collected through one- and two-way laser pulse transmission. It lies in that laser impulses of an SLR station are registered in a ground standard's time scale and then transferred to a satellite where they are registered in its time scale and reflected back to the SLR station by a retroreflector system. Using the impulses registered at the satellite, one can determine the one-way pseudorange, and using an interval between the moments of impulse emission and its arrival at the SLR station, one can determine the true two-way range. Differences between these two ranges determine a shift in the timing between a satellite's (on-board) and ground standard's time scales. Upon that, the impacts of movements of both the satellite and SLR station relative to each other which take place over the time of laser impulse distribution should be compensated (i.e. ballistic ranging corrections should be introduced), as well as relativistic corrections should be introduced; besides of that, when it comes to both the satellite and SLR station, one should consider all the instrument delays of electric and optical signals and all the delays of signal cable distribution.

In April 2013, the GLONASS-131 equipped with optical retro-reflectors and on-board hardware for LTT registration was launched.

To implement and use LTT, three SLR stations modified for such functioning were used: base laser station in the Moscow region, laser station 1868 («Komsomolsk») and laser station 1879 («Altay»).

The modification of the SLR stations consisted in installation of hardware for high-precision registration of laser impulse start moments in the time scales of external time standards remoted from the SLR stations within 2 km with the error at the level of 10^{-11} s. The extra hardware was labeled as «GS-LTT» (see Figure 1).

In October 2015, we have included the SLR station 1874 («Mendeleevo-2») modified in the same way into the tests; this station is located within the territory of the Russian state time and frequency standard and conjugated with the UTC (SU).

The distance between the base SLR station and «Komsomolsk» is about 6000 km. The distance between the base SLR station and «Altay» is about 3000 km. The «Mendeleevo-2» station is located in the Moscow region within 50 km from the base laser station.

Upon quasi-simultaneous determination of the divergence between the time scales of two SLR stations and a satellite the divergence between the ground time scales is determined as the algebraic difference between collected divergences. An interval of quasi-simultaneousness between collation sessions is determined by a short-term instability of the on-board time and frequency standard as follows:

$$\delta t \leq \frac{\delta f}{f} \cdot \Delta T,$$

where:

δt – permitted error for comparing the ground standards ($\delta t \leq 100$ ps);

$\frac{\delta f}{f}$ – short-term instability of the on-board standard's frequency

ΔT – time interval taking place between collation sessions for the first and second ground standards.

A scheme of time transfer tests is presented on Figure 1.

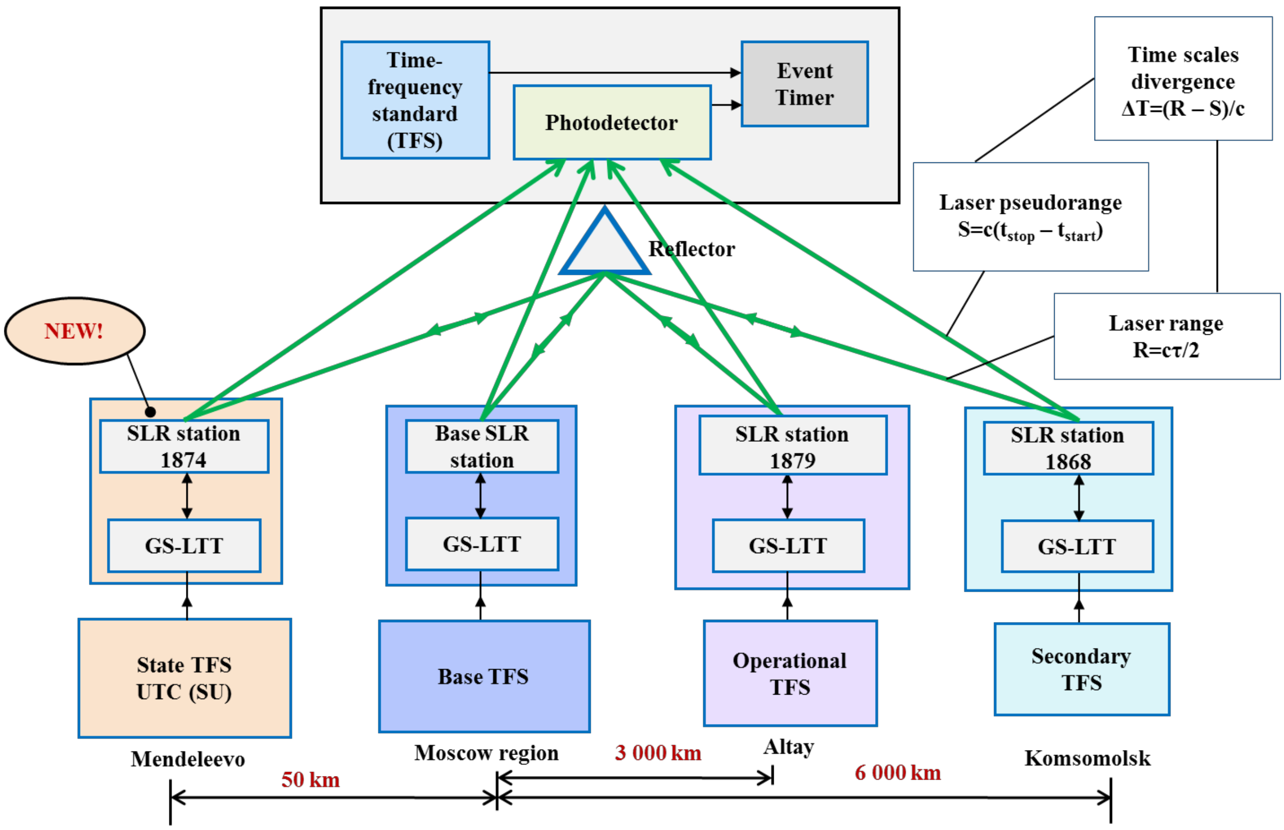


Figure 1. Scheme of tests on time scales transfer

A diagram of the LTT ground segment is presented on Figure 2.

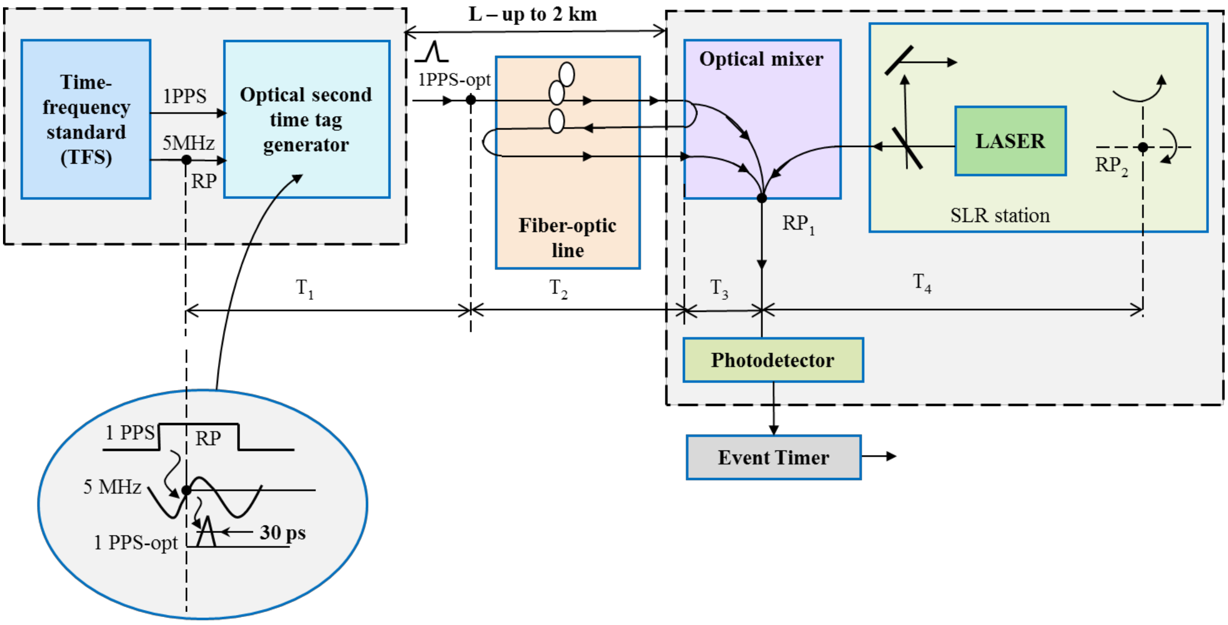


Figure 2. Diagram of the LTT ground segment's hardware being tested

Where: T_1 – calibrated and thermostated; T_2 – measured every second using the loop method; T_3 – calibrated; T_4 – calibrated, determined by the SLR telescope construction and optical mixer's location in the SLR station.

Purpose of the ground segment: determination of laser impulse emission moments in the time scale of an external time standard with the error of about 10^{-11} s.

A diagram of the LTT on-board segment is presented on Figure 3.

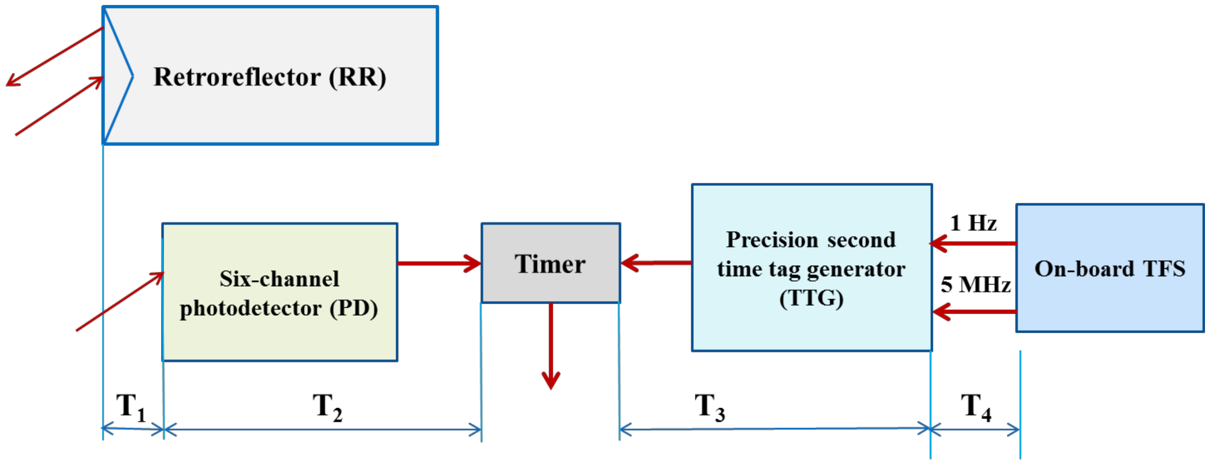


Figure 3. Diagram of the LTT on-board segment

Systematic error sources of the LTT on-board segment are the following:

T_1 – total geometrical delay which depends on the interposition of the photodetector and retroreflector ($T_1^{(1)}$), ground station sight line direction and photodetector channel number ($T_1^{(2)}$); T_2 – photodetector delay (depends on the signal amplitude and photodetector temperature); T_3 – time tag generator delay (depends on the temperature); T_4 – cable delay.

Purpose of the on-board segment: laser impulse reflection for laser ranging, laser impulse receive and its further tying to the on-board time scale with the error of about 10^{-11} s.

The error budgets of the LTT ground and on-board segments are given in Tables 1 and 2.

Table 1. LTT ground segment's error budget

Error source	Random component of a one-time measurement, ps	Time delay calibration error, ps
Optical second time tag generator	**25**	**10**
Fiber-optic communication line	**35**	**23**
Optical mixer	**-**	**15**
SLR calibration correction	**-**	**15**
Event timer	**35**	**-**
TOTAL:	**56**	**33**

Table 1. LTT on-board segment's error budget

Error source	One-time measurement RMS σT_i, ps	Systematic error T_i, ps
PD and RR spatial distribution on a satellite ($T_1^{(1)}$)	**-**	**≤ 20**
Ground station sight line directions change ($T_1^{(2)}$)	**-**	**≤ 5**
PD delay (T_2)	**≤ 70**	**≤ 110**
TTG delay (T_3) and timer count discreteness	**≤ 54**	**≤ 50**
Radio frequency cable delay	**-**	**≤ 10**
TOTAL:	**≤ 90**	**≤ 123**

The largest random error is introduced by the SLR station, which is conditioned by the quite high (250-300 ps) laser pulse duration. Laser signals registered both on-board and on the ground are multielectron. The measurement error related to the laser pulse duration is minimized by using riding threshold circuits.

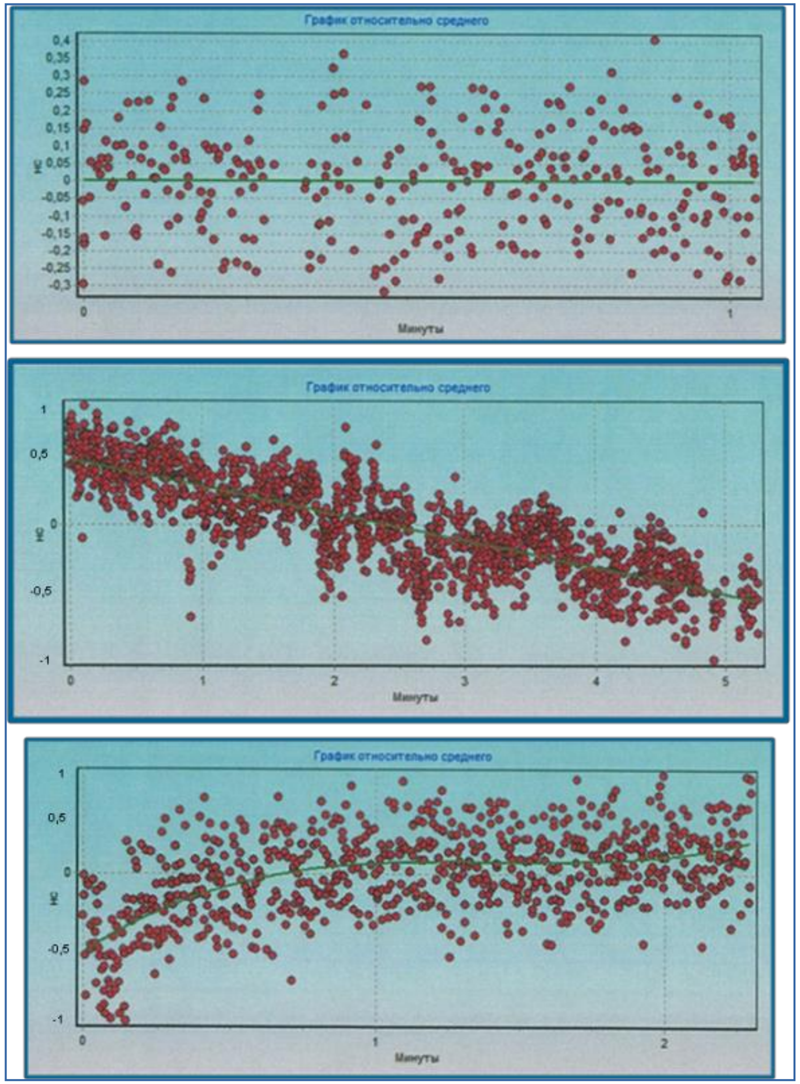
Speaking of the promising hardware, it is planned to increase the accuracy of measurements more than 2 times, particularly but not exceptionally as a result of using lasers with the laser pulse duration less than 50 ps in SLR stations.

An error budget for LTT determination of divergence between the on-board and ground time scales is given in Table 3.

Table 3. Error budget for LTT determination of divergence between the on-board and ground time scales

Error source	One-time measurement random component, ps	Delay calibration error, ps
On-board segment	**90**	**123**
Ground segment	**56**	**33**
SLR	**240**	**50**
TOTAL:	**262**	**137**
Upon averaging on the interval of 30 seconds	**26**	**137**

According to the test results, the random error of one-time measurements of divergence between the on-board and ground time scales is in the range of 82-190 ps, and upon averaging on the intervals (of 2 and 30 s) — 36-86 ps. An example of quasi-simultaneous collation of the time scales of distributed ground standards and the GLONASS-131 satellite is given on Figure 4.



Altay – GLONASS-131

24.08.15, start – 20:50, stop – 20:52

$RMS_1 \leq 147$ ps (one-time measurement)

Moscow – GLONASS-131

24.08.15, start – 21:01, stop – 21:09

$RMS_1 \leq 187$ ps

Komsomolsk – GLONASS-131

24.08.15, start – 21:09, stop – 21:11

$RMS_1 \leq 153$ ps

Figure 4. Example of collecting quasi-simultaneous measurements for collation of the GLONASS-131 and standards' time scales

The main limiting factors of data collection availability are need for the night time, weather conditions and ballistic restrictions for quasi-simultaneous observation of a single satellite.

There are a few ways to overcome these factors, namely:

1. Making laser stations function in 24/7 mode of operation.
2. Expansion of the on-board network based on equipping all the new GLONASS satellites with the LTT hardware.
3. Creating a ground network of distributed laser stations equipped with GS-LTT and hydrogen frequency standards; each such station can operate as an intermediate time standard upon synchronizing its time scale with the base or state time standard. Further time scale offset can be predicted in accordance with this time standard frequency drift polynomial.

Thus, creating a distributed network of stations placed in different weather conditions and having intermediate time standards can dramatically increase the availability of prompt LTT between a satellite and ground time standards.

As an important extra measure, the «Tochka» station features its complexation with a GNSS GLONASS all-weather radio pseudoranging and monitoring station which is regularly calibrated using laser pseudoranging measurements.

On top of this, the SLR and radio monitoring stations should operate in a single time scale and have accurate geodetic ties.

To provide LTT accuracy using a calibrated radio station, it is necessary to implement the following things:

- use of precision ranging data from SVOEVP (System of High-Precision Determination of Ephemeris and Time Corrections) [1];
- use of double-frequency radio measurement methods in order to compensate the ionospheric impact on phase ranging accuracy;
- prompt use of data collected from water vapor radiometers to minimize «humidity» of the tropospheric signal distribution delay;
- prompt use of data on the actual satellite time scale offset determined through the PPP technology. [2]

The conducted tests on collation of the time scales of four distributed ground time standards using the GLONASS-131 navigation satellite have confirmed that it is possible to achieve LTT with the error of no more than 100 ps.

References:

Pasynkov V. V., *Status and prospectives of the global precision navigation systems*, collected papers of the XXII Saint Petersburg International Conference on Integrated Navigation Systems, p. 417-421, Saint Petersburg, 2015.

Shargorodskiy V. D., Fedotov A. A., Pasynkov V. V. and others, *System of high-precision determination of ephemeris and time corrections*, Vestnik GLONASS, p. 58-62, Moscow, 2012.