Methods for Coordinate and Time Data Collection in the Laser Station «Tochka»

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The authors have analyzed satellite laser ranging development trends and defined requirements for SLR-stations used for ephemeris-time measurements in GNSS. The paper represents technical characteristics of the laser station «Tochka» designed for precision laser ranging and ephemeris-time measurements in the GLONASS system.

The authors have also reviewed technical solutions enabling high accuracy of measurements and methods to calibrate laser station equipment and provided the results of experimental development of a laser transfer technology as applied to the time scale of the State time and frequency standard; also, they have shared the plans for production of the laser stations «Tochka» and their further installation within the territory of Russia and abroad.

Introduction

Analysis of SLR development trends determines the wisdom of dividing the modern SLR stations into two main groups by the purpose of the collected precision measurement data:

- for completion of the fundamental and applied tasks of space geodesy and geodynamics, including those studied within GGOS;
- for increasing the accuracy of ephemeris-time support (ETS) for the global navigation satellite systems (GNSS).

Laser stations of the 1st type generally measure the range to SC laser reflectors. New stations of the 2nd type simultaneously collect both precision laser ranging and laser pseudoranging data, as well as radio pseudoranging measurements on GNSS navigation signals.

To take ephemeris-time measurements in GNSS, stations of the 2nd type are additionally equipped with a GNSS navigation signal receiver, while GNSS navigation satellites must be equipped with photodetecting modules to link laser pulse arrival times to the onboard clock time scale [1].

Such a module has been installed on «Glonass-747», and there are plans to install the same modules on the next navigation SC «Glonass» to be launched. Collecting coordinated laser and radio measurements enables stations of the 2nd type to complete 3 basic tasks in GNSS:

- GNSS spacecraft orbit determination and monitoring by laser ranging;
- determination and monitoring for divergence between the onboard and ground time scales using laser and radio pseudoranging under any weather conditions;
- calibration of hardware delays in primary code and phase navigation measurements and their combinations.

Requirements for SLR-stations used to take ephemeris-time measurements in GNSS

One of the key requirements for SLR-stations used for ephemeris-time measurements in GNSS is a high performance rate.

The ILRS global experiment «LARGE» on laser tracking GLONASS, GPS, Galileo and Beidou navigation spacecraft equipped with retroreflectors demonstrated that, considering low performance rates of the most SLR-stations and extremely low number of daytime measurements, the participants had managed to build a high-accuracy laser orbit comparable with radio ones in terms of accuracy upon decreasing the number of SC monitored by the whole ILRS network from 38 to 6.

Table 1 represents performance rates of some ILRS stations working on GNSS navigation SC per year (according to Global Performance Report Cards data):

Table 1

Station	**YARL**	**CHAL**	**GODL**	**GRZL**	**MATM**	**WETL**	**ALTL**	**BRAL**	**KOML**
Total number of NP on GNSS	**25 469**	**20 664**	**5744**	**14 266**	**8 006**	**10 236**	**6 993**	**6 628**	**6 232**
Number of NP on GNSS per day	**69.8**	**56.6**	**15.8**	**39.1**	**21.9**	**28.1**	**19.2**	**18.1**	**17.1**

For laser stations given in the table, daily performance rate varies from 20 to 70 NP.

Considering severe requirements for laser measurement data volumes necessary to increase the accuracy of completion of various GNSS ephemeris-time tasks, the key strategy for GNSS satellite tracking for every station is to take measurements on all GNSS satellites passing through the service area of a station.

If one presumes that, when the sky is clear, each station working on GNSS must produce one normal point every 15 minutes per each navigation spacecraft in the service area of a station, then the performance rate under clear sky conditions must reach 576 NP per 24h. Considering weather conditions (open sky probability is 0.4), this complies with an average daily performance rate of about 200 NP per 24h. In fact, meeting this requirement means that in order to provide full-fledged performance on GNSS, a station cannot be involved into completion of any other measurement tasks.

The main reserve to increase performance rates of laser stations is decrease of the time spent on collecting NP data at the expense of the station performance frequency increase or installation of double-spot circular retroreflectors featuring a minor signature on the GNSS satellites [2].

Other mandatory requirements for stations used for ephemeris-time measurements in GNSS are the following:

- equivalent station performance under both night and day conditions;
- providing photodetector operation in a single-electron reception mode;
- precise laser beam pointing system calibration;
- precise laser ranging channel calibration;
- precise laser pseudoranging channel calibration;
- station performance automation.

All these requirements are met by the radio-laser station «Tochka» designed for precision ranging and pseudoranging, highly accurate time transfer between remote ground frequency-time standards and ephemeris-time measurements in GLONASS.

Methods for coordinate and time data collection in the laser station «Tochka»

A simplified functional diagram of the laser station «Tochka» is illustrated on Figure 1:

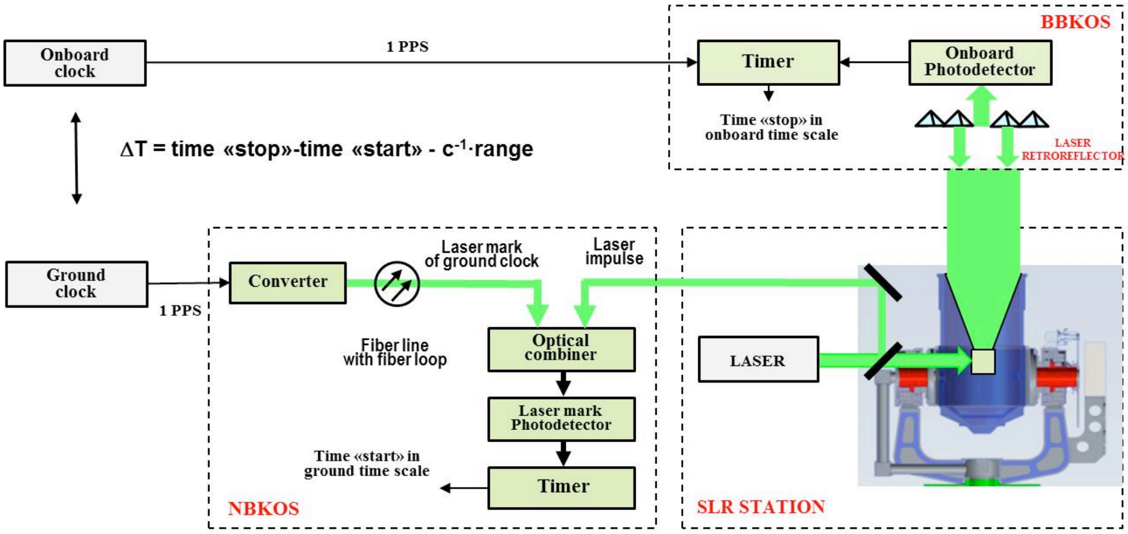

Fig. 1 Functional diagram of the laser station «Tochka»

The time measurement technology, including precision time transfer, is implemented through equipping a laser rangefinder with a module called NBKOS which measures laser pulse start time in the external frequency-time standard's time scale.

Laser pulse arrival time in the onboard frequency-time standard's time scale is measured by an onboard optoelectronic module called BBKOS installed on the GLONASS satellites.

Divergence between the onboard and ground time scales is determined as a difference between the pulse arrival and start times with the deduction of the range (measured by the station) divided by the speed of light. For time transfer between ground frequency-time standards, it is necessary to simultaneously or quasi-simultaneously determine divergences between the time scales of two ground standards in relation to the same onboard time scale.

The onboard module includes photodetecting unit and timer. The ground module includes optoelectronic unit converting 1PPS signals of an external frequency-time standard to laser time tags not exceeding 30 ps in duration, fiber-optic communication line to transfer a laser tag to the station, as well as optical combiner, photodetector and timer.

Methods for coordinate and time data calibration in the laser station «Tochka»

Absolute accuracy of coordinate and time measurements is provided through calibration of hardware delays of the ground module, laser rangefinder and onboard module and further keeping calibrations up to date. The laser rangefinder and ground module calibration pattern is shown on Figure 2.

Calibration of coordinate and time measurements is provided mainly through laser aids and precision event timers. Ranging channel calibration is performed continuously through standard calibration distance measurements simultaneously with ranging to navigation spacecraft.

Ground module calibration is also performed continuously through measurement of laser time tag (mark) delays inside the fiber-optic line in relation to a laser loop tag. Also, there is a separate calibration of a delay between the laser time tag and 1PPS impulse of an external time standard inside the converter.

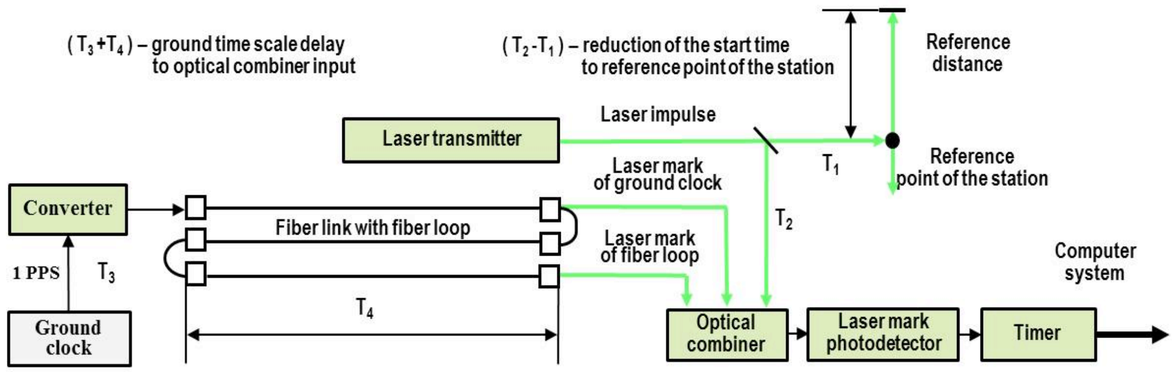

Fig. 2 Laser rangefinder and ground module calibration pattern

The onboard module calibration pattern is shown on Figure 3. Onboard module is regularly calibrated using the laser diode launched by 1PPS pulses of the onboard frequency-time standard, considering a launch line delay.

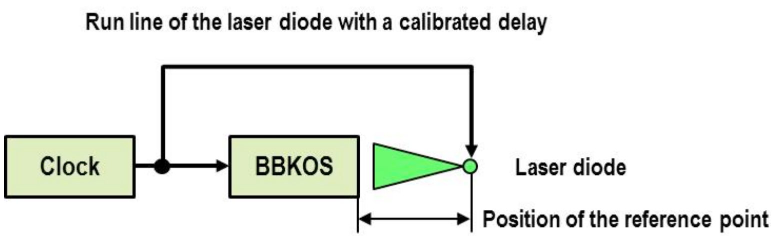

Fig. 3 Onboard module calibration pattern

Coordinate and time data calibration accuracy in the laser station «Tochka»

Coordinate and time measurement accuracy evaluations, including time transfer ones, were obtained over the period of 2014-2015. Accuracy evaluations were obtained as a result of both ground tests of equipment and a number of experiments aimed at measuring the divergence between the onboard and ground time scales among selected laser stations equipped with ground modules and an SC «Glonass-747» equipped with the onboard photodetecting unit. The results are given in Table 2:

Table 2

System component	Random error of a single measurement, no greater than	Residual systematic error of measurements, no greater than
Ground module	**20 ps**	**30 ps**
Onboard module	**80 ps**	**60 ps**
Laser rangefinder	**50 ps**	**10 ps**
Total	**96 ps**	**65 ps**
Total on the averaging interval of 30 s	**10 ps**	**65 ps**

Note: Table 2 gives evaluations of errors reduced to the pulse duration of the 50 ps laser used in «Tochka».

The random component of a single laser pulse start time measurement error in the station's time scale does not exceed 20 ps. The random component of a single laser pulse arrival time measurement error in the onboard time scale does not exceed 80 ps. The random component of laser rangefinder error does not exceed 50 ps. On the aggregate, taking an averaging time of measurements equal to 30 s, the random component of the complete time scale divergence measurement error does not exceed 10 ps.

Residual systematic error of onboard laser pulse arrival time measurement module calibration does not exceed 60 ps. On the aggregate, the complete systematic component of the time scale divergence measurement error does not exceed 65 ps.

Results of experiments on laser transfer of the State primary frequency-time standard's time scale

In 2015, the laser station «Mendeleevo» based at «VNIIFTRI» was equipped the ground module for laser pulse send registration in the State frequency-time standard's and UTC (SU) time scales. Over the period from 23.03.2016 to 23.04.2016, we have conducted the first space experiments on transfer of the UTC (SU) time scale to the GLONASS system time scale standard using laser aids. The primary goal was to compare standard's time scale divergence measurements in relation to UTC (SU) taken through the «common view» method using radio aids for collation and laser measurements. The results of this comparison are represented in Table 3:

Table 3

Date	$\Delta T_{UTC (SU) - CS / laser}$	$\Delta T_{UTC (SU) - CS / radio}$	$\Delta\Delta T_{UTC (SU) - CS}$
23.03.2016	**26669.2 ns**	**26680.2 ns**	**+11.0 ns**
21.04.2016	**26659.9 ns**	**26675.2 ns**	**+15.3 ns**
23.04.2016	**26658.6 ns**	**26668.5 ns**	**+9.9 ns**
Mean deviation			**+12.1 ns**

According to measurement data, in each case the results obtained by both laser and radio aids for time collation differ at the level of 12 ns on the average. The accuracy of laser equipment used over the course of the experiment is estimated to be no greater than 0.3 ns.

The GLONASS system time scale shift difference in relation to UTC(SU) ob-tained using the data collected from laser and radio aids is considered as a calibration correction for measurements of radio aids for determination of GLONASS system time scale divergence in relation to UTC(SU).

Results of the ground try-out and conducted experiments allow us to confirm that the time measurement technology has successfully passed evaluation tests and at the present time is at the stage of integration to the GLONASS system.

Plans on production and further global distribution of the laser stations «Tochka»

The first 3 laser stations of the «Tochka» type are planned to be built and placed at the Russian sites in Mendeleevo (Moscow Oblast), in Irkutsk and Petropavlovsk-Kamchatskiy in 2017.

We are currently planning to produce 4 more stations of the «Tochka» type and install them within the foreign territories until 2020. At the present time, we are reviewing Mexico, Indonesia (Java Island), French Polynesia (Tahiti) and Argentina. Besides of that, we also consider an opportunity to place these stations in Israel and New Zealand.

Conclusion

Experimental development of the laser time measurement technology in GLONASS and time transfer using onboard equipment of the GLONASS navigation SC proves that it is possible to use this technology for time transfer over long distances with an absolute error of no greater than 0.1 ns.

Considering severe requirements for laser measurement data volumes necessary to increase the accuracy of completion of GNSS ephemeris-time tasks, the key strategy for GNSS satellite tracking for every station is to take measurements on all GNSS satellites passing through the service area of a station.

The laser station «Tochka» meets all the requirements for stations designed for ephemeris-time measurements in GNSS.

In order to provide solution for fundamental and applied tasks of space geodesy and geodynamics simultaneously with continuous data collection for GNSS coordinate-time support accuracy increase tasks, it is reasonable to equip laser tracking sites with two SLR-stations (1st and 2nd types) which is crucial in connection with GGOS project development.

REFERENCES

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