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The concept and preliminary results of use of satellite laser ranging for GLONASS accuracy improvement

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Abstract. *The concept of use of combined laser range and pseudorange measurements for improvement of accuracy of geodetic, ephemeris and time-frequency parameters formation in the space segment of the Russian navigation system GLONASS is presented.*
Composition and technical parameters of modernized laser stations designed for operation in GLONASS ground segment are presented. Composition and technical parameters of on-board laser systems for laser measurements of range and pseudorange between laser stations and GLONASS S/C, as well as for laser measurements between GLONASS S/C are presented.
Methods of laser measurements use are presented for:
- improvement of accuracy of definition and check of the difference between onboard and ground time scales;
- calibration of hardware and inter-frequency delays in onboard navigation systems and navigation receivers;
- definition and check of geodetic data necessary for refinement of GLONASS geocentric coordinate system and its reference to international coordinate system ITRF;
- check of accuracy of ephemeris-time data of navigation message and geodetic data of GLONASS measurement systems.
Experimental data obtained during spaceflight testing of the Inter-satellite laser navigation and communication system and laser range and pseudorange measurement system as well as onboard and ground time scales difference data with the use of equipment installed on S/C GLONASS-728 and GLONASS-747 are considered.

The goal of using laser measurement systems in the structure of Russian navigation system GLONASS, as shown in Figure 1, is provision of GLONASS with high-accuracy geodetic and ephemeris-time data.

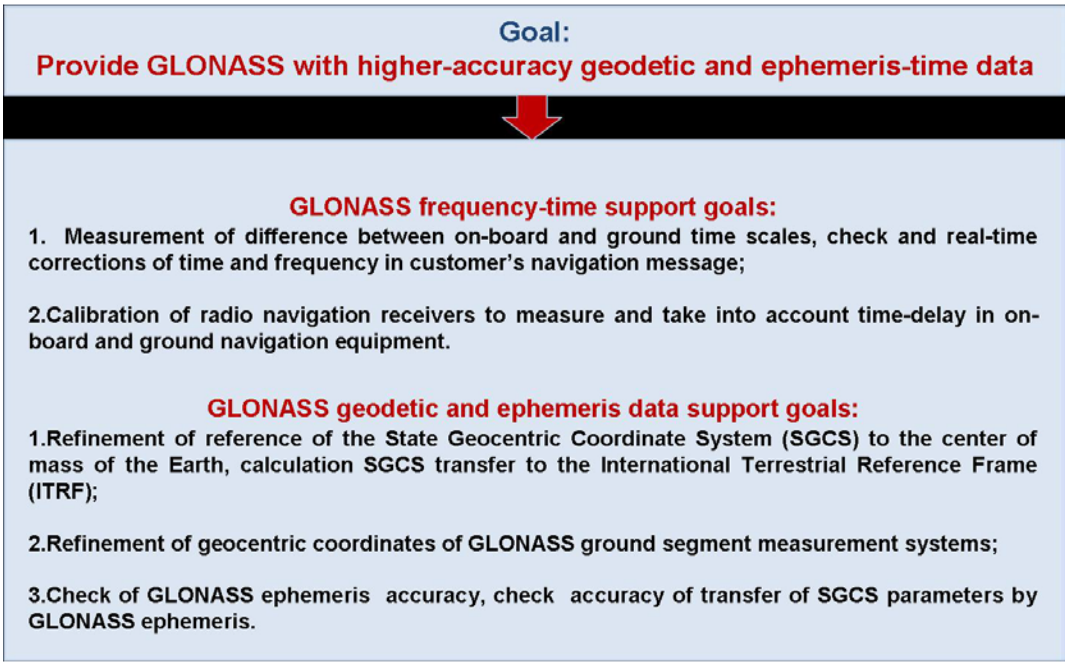

Figure 1 The goals of using laser measurement systems in the structure of GLONASS

Laser systems are used for time-frequency support for:

- measurement of difference between onboard and ground time scales, check and real-time correction of time-frequency parameters of navigation message;
- calibration of radio navigation receivers to measure and take into account hardware latency in on-board and ground navigation equipment.

In geodetic and ephemeris support, laser systems are used for:

- refinement of reference of the Federal Geocentric Coordinate System (FGCS) to the center of mass of the Earth, calculation of reference parameters between FGCS and the international terrestrial reference frame (ITRF);
- refinement of geocentric coordinates of GLONASS ground segment measurement systems;
- check of formation accuracy of GLONASS ephemeris, check of accuracy of passing of FGCS parameters by GLONASS ephemeris.

To solve these problems, the existing laser stations shall be modified, and space segment shall be augmented with laser measurement systems for measurements between ground station and navigation spacecrafts (S/C) and between two navigation S/C.

Modification of laser stations, as shown in Figure 2, used for ground segment consists of augmentation of the stations with the following equipment:

- hydrogen clock with daily instability of not worse than $2 \cdot 10^{-15}$;
- ground module for pseudorange measurements that provides accurate reference of laser pulse radiation moment to the hydrogen clock time scale;
- double-frequency geodetic-class navigation receiver linked to the hydrogen clock time scale;
- water vapor radiometer and weather station to take into account influence of the atmosphere on propagation time of radio and optical signals.

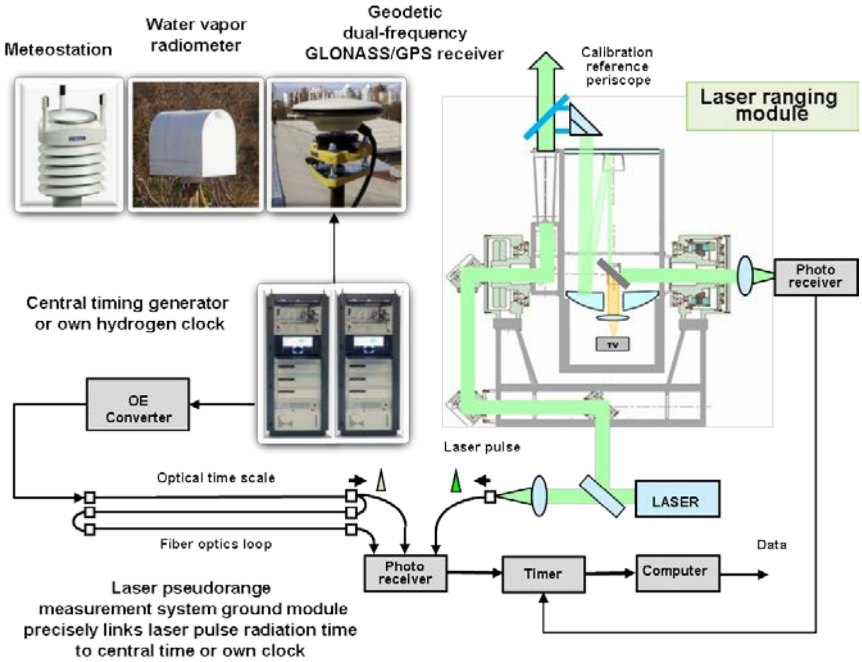

Figure 2 Composition of modernized laser stations designed for operation in GLONASS ground segment

Requirements to technical parameters of the modified stations are set to ensure laser ranging at 3 mm level of accuracy at present time (and 1 mm in the near future). Laser and radio measurements of pseudorange have to be with errors at the level of 50 ps (20 ps in perspective).

During selection of laser stations locations preference was given to locations with well-developed infrastructure and good weather conditions. In addition to currently operating 10 laser stations, it is foreseen to bring 6 more stations to operation in 2014-2015, as shown in Figure 3. Locations and number of stations were selected in such a way that at any given moment at least 5 stations would be able to perform observations and every pair of stations would have an ability to compare their time scales at least once a week.

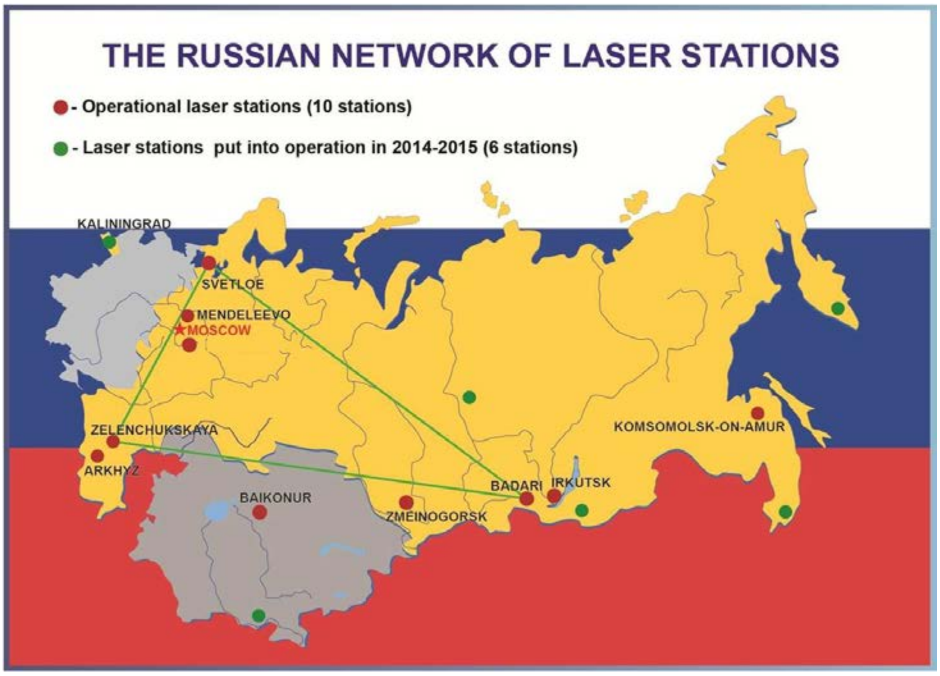

Figure 3 The Russian network of laser stations

Composition of onboard laser systems, as shown in Figure 4, place on each GLONASS S/C :

- circular retroreflector system;

- on-board pseudo-range measurement system module;
- two modules of inter-satellite laser navigation and communication system.

Circular retroreflector system presently has effective area of about 100 million m^2, and in perspective will be replaced with circular retroreflector system with effective area of about 160 million m^2, consisting of corner cube reflectors with sides that form two-spot reflection pattern.

To solve geodetic problems, ground laser stations also have to perform range measurements of geodetic S/C, in particular LAGEOS and BLITS.

On-board module of laser pseudorange measurement system (LPMS) measures time of laser pulses arrivals in the onboard time scale. These measurements are transmitted via radio link to the system control center and to the system of high-accuracy determination of ephemeris and time corrections, which calculates pseudorange and difference between on-board and ground time scales using data from the ground module for pseudorange measurements.

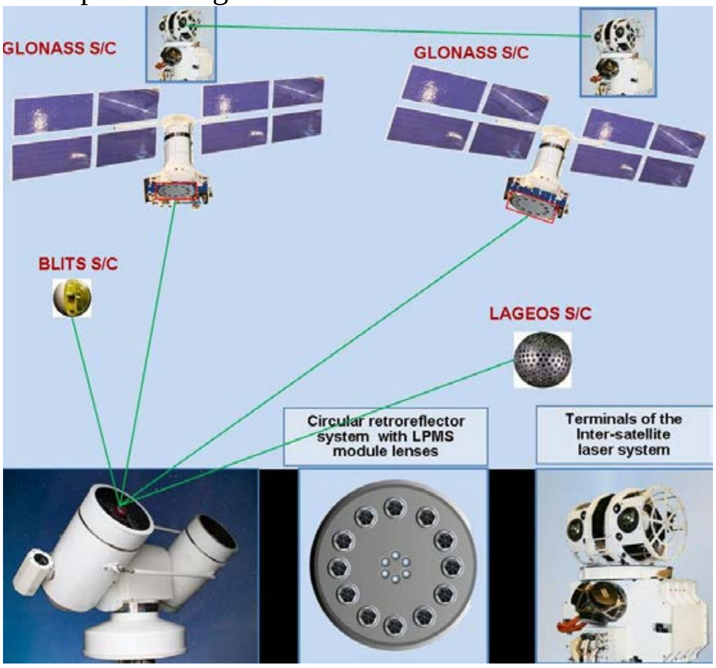

Figure 4 Composition of onboard laser systems designed for operation in GLONASS space segment

Modules of inter-satellite laser navigation and communication system provide mutual measurements of pseudorange and use these measurements to find difference of onboard time scales as well as distances between navigation S/C of the constellation. Technical parameters of the on-board modules and acceptable measurement errors are selected to ensure determination of time scales difference at the level of 0.1 ns for inter-satellite measurements and 0.02 – 0.05 ns when combined with ground laser systems.

Goals and methods of use of laser systems for GLONASS time and frequency support are:
- inter-satellite laser navigation and communication system is used for real-time correction of a navigation message time and frequency corrections for improvement of customer’s navigation. This goal is achieved by direct measurements of pseudorange between navigation S/C, by mutual data exchange and calculation of on-board time scales difference and inter-satellite pseudorange;
- laser range and pseudorange measurement systems are used for measurements between ground station and navigation S/C for implementation of distributed network of ground stations with a single time scale, for check of accuracy of formation of time and frequency corrections of navigation message and for calibration of one-way and two-way radio systems during their operation. This goal is achieved by measurement of time scale difference between remote stations using difference of their divergence from onboard time scale of the same navigation S/C, by determination of difference between navigation S/C time scale and GLONASS system time scale

using laser range and pseudorange measurements, and by comparison of laser pseudorange and range with radio pseudorange and range.

Goals and methods of use of laser systems for GLONASS ephemeris and geodetic support are:

- laser range measurement system is used for refinement of linking of Federal Geocentric Coordinate System (FGCS) to the center mass of Earth, as well as correspondence of reference parameters of FGCS to ITRF, refinement of geocentric coordinates of GLONASS ground segment stations, check of FGCS parameters accuracy in GLONASS ephemeris and check of accuracy of GLONASS ephemeris formation.
- this goal is achieved by determination of ground stations coordinates using laser ranging measurements to S/C LAGEOS and BLITS and their comparison with coordinates of the same stations obtained from laser ranging of GLONASS and ephemeris data of its navigation message and by comparison of laser range measurements with projection of navigation S/C ephemeris on slant distance.

Flight testing for refinement of system for laser measurements of pseudorange and difference between onboard and ground time scales is being carried out at present time. S/C GLONASS-M # 747 with onboard module of pseudorange measurement system and three laser stations with ground modules of the same system take part in this flight testing.

S/C GLONASS-M started on 26.04.2013. Transition of onboard systems from orbital standby to nominal mode was successfully performed on 27.05.2013. At present time, first stage of testing (10 measurement sessions) has been completed. Main results of the first stage of testing are:

- energy characteristics of the measurement channel between ground station and onboard module were confirmed. In GLONASS tracking by the laser station using ephemeris, probability of reception of a laser pulse onboard was 0.98 – 0.99 in clear weather;
- in two sessions, a stable reception of laser pulses with detection probability of each pulse of 0.3-0.4 onboard the S/C with overcast in the proximity of the ground station was achieved. This effect is discovered for the first time and if it is confirmed, it can be used for significant improvement of the efficiency of ground laser station measurements of pseudorange;
- confirmed accuracy parameters of onboard and ground equipment. Analysis of data shown in Figure 5 shows that error of “raw” measurements of time scales difference is about 140 ps, and error of measurements averaged at 30 s intervals is about **37 ps**.

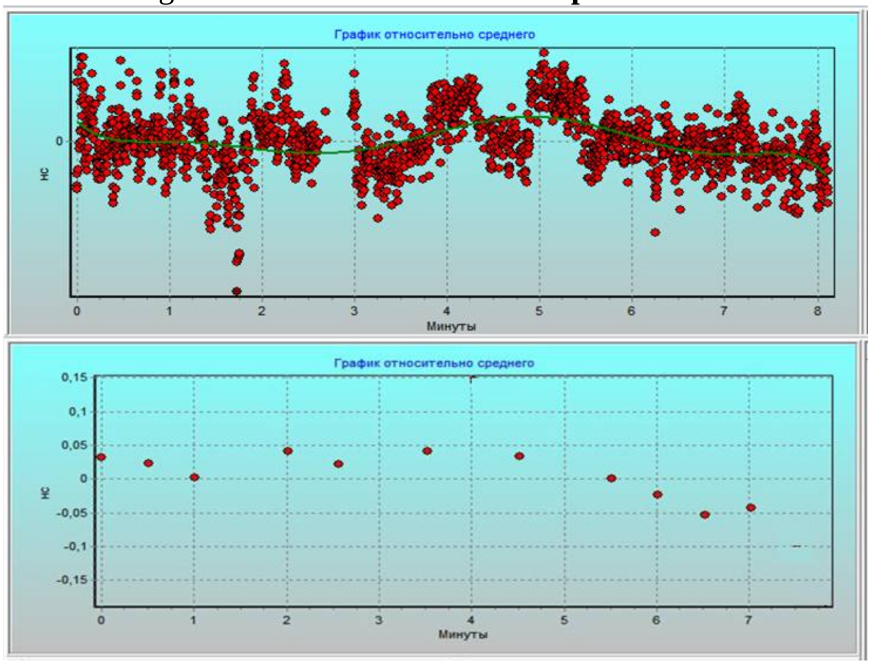

Figure 5 Accuracy estimation of “raw” and averaged at 30 s intervals measurements of difference between onboard time scale of GLONASS № 747 and laser station time scale

Slightly earlier, in 2011-2012, flight testing of the inter-satellite laser navigation and communication system was performed. Its module was installed onboard the S/C GLONASS # 728, and its ground module – at the laser station of Altay optical-laser center. The following activities were performed during flight testing:

- refinement of standard algorithms for search and mutual tracking by onboard module;
- measurement of mutual pseudoranges;
- processing of measurements and accuracy evaluation of range measurements and relative difference between onboard and ground time scales.

Processing results of performed measurement sessions are:

- RMS error of measurements of time scales difference at one-second averaging interval was 0.19 – 0.23 ns with processing of 17 pulses minimum;
- if number of processed pulses was increased to 60, RMS error of time scales difference measurements was 0.1 ns.

Thus, space flight testing of the inter-satellite laser navigation and communication system and laser pseudorange measurement system in the path “ground – navigation S/C GLONASS” showed feasibility of use of laser systems for provision of GLONASS with high-accuracy geodetic and ephemeris-time data.