# DEVELOPMENT STAGES OF STATIONS, NETWORKS AND METHODS OF SLR APPLICATION FOR GLOBAL SPACE GEODESY AND NAVIGTION SYSTEMS

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*The presentation discusses main stages of development of Russian SLR stations, networks and methods of their application for geodetic, ephemerides-time and metrological support of various space systems, first of all navigation-geodetic ones.*

## SLR stations of pilot stage

First application of lasers for domestic lunar program was related to necessity of accurate determination of "Lunokhod-2" (Fig.1) selenographic coordinates. It had a laser photo receiver onboard. A ground telescope ø = 0.5 m with ruby laser and beamwidth 2" was scanning Le Monnier crater while simultaneously photographing it, with time stamp and registration of laser beam target point which was determined using corner cube reflectors installed at the point of laser beam exit from the telescope.

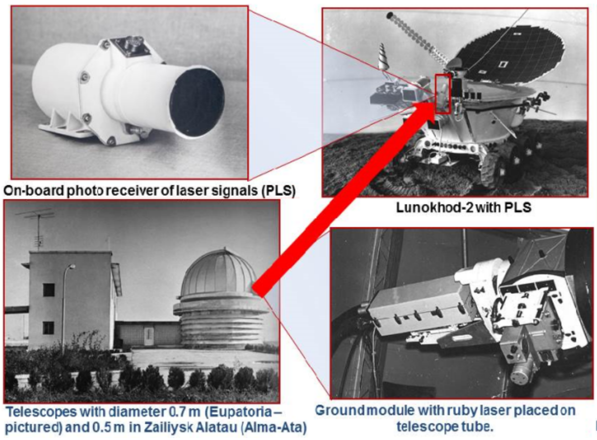


Fig.1 Laser direction-finding of "Lunokhod-2"

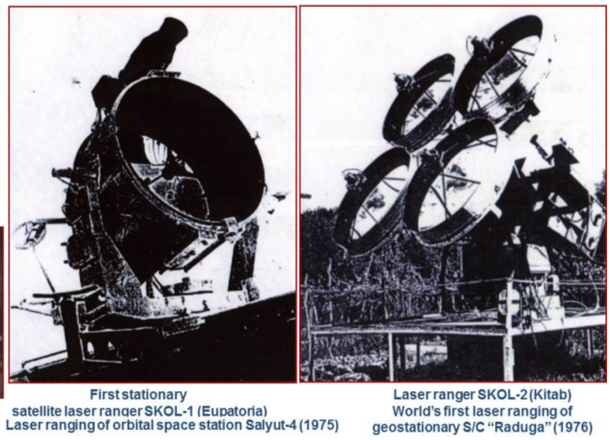


Fig.2 First pilot SLR stations

Processing of the photographs corresponding to telemetry receipts of the photo receiver with moments of laser beam registration (about 1000 instances) allowed to determine average selenographic coordinates of "Lunokhod-2" with the accuracy of 0.1 arc second, or 200 m on the Moon surface.

In the same experiment, there was performed the first transmission of information in the laser line Earth-Moon using time-pulse modulation of laser pulses. It was the *first work* (1973) of one-way technology of using lasers with registration of moments of pulse arrivals in the on-board time scale.

At the initial stage, experimental laser rangers SKOL-1 and SKOL-2 were created with ruby lasers and searchlight mirrors for reception. They allowed, in addition to ranging of low-orbit S/C ("Salyut-4" in 1975), to perform world's first laser ranging of two geostationary satellites ("Raduga" in 1976) equipped with laser retroreflectors (Fig.2).

## Russian SLR station networks for space geodesy and navigation

A network of 20 SLR stations "Sazhen-2" (YAG lasers) was developed and established in 1985-1988 for the astronomy-geodetic stations that worked with "GEO-IK" S/C (Fig.3).

"Saszen-2" was the *first domestic* commercial satellite laser ranger accepted for permanent operations to solve problems of space geodesy.

During the same period of time (1980-1985) one of the world's largest optical laser station was created (SLR station "Sirius") at the site on top of Maidanak mountain (Pamir Mountains) with the best astronomical climate parameters on Eurasian continent (Fig.4).

*World's first* laser ranging of Global Navigation Satellite System (GLONASS) S/C was done at this site in 1982, distance about 20000 km.

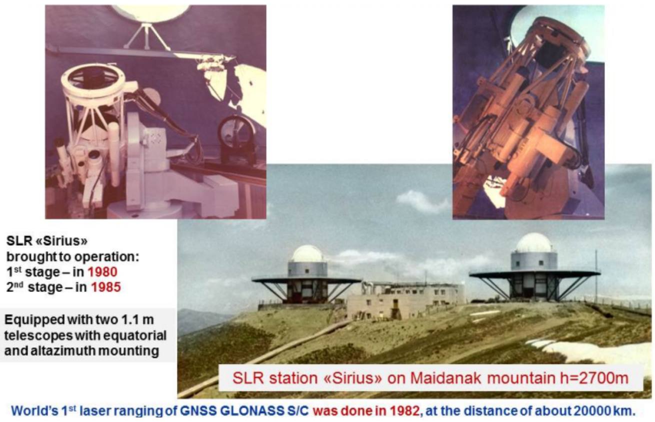


Fig. 3 SLR stations "Sazhen-2" Fig.4 SLR station Maidanak

Standard use of SLR stations for global navigation satellite systems (GNSS) first started after a network of four SLR stations "Sazhen-S" was established in 1987-1990 for calibration (exclusion of systematic errors) of two-way radio systems of the 1st generation of GLONASS satellites.

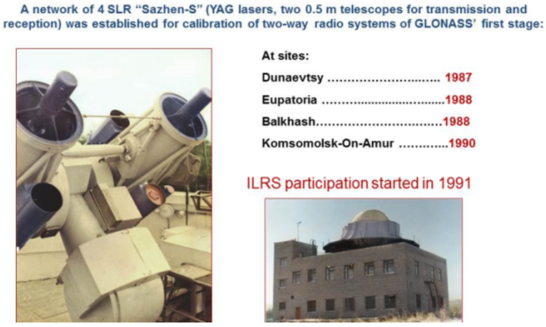


Fig.5 SLR station "Sazhen-S"

Russian SLR stations participate in ILRS geodetic and geodynamic projects since 1991. At present time, coordinates of three stations (Altai, Baikonur, Komsomolsk-On-Amur) are used as reference ones in the ITRF.

Stationary SLR stations "Sazhen-T" with improved accuracy were developed and brought to operation in the interests of "GLONASS-M" second generation S/C at sites near Moscow, at Altai optical-laser (Fig. 6) and at Baikonur Cosmodrome (Fig.7).



Fig. 6 Fig. 7

For expansion of geographic coverage and improvement of climate resistance of Russian SLR network, in 2005 there was developed and *serial* production started of a compact, modular, fast-deployable SLR station "Sazhen-TM" with sub-centimeter accuracy (Fig.8), that became a foundation for modern Russian geodetic and navigation SLR networks.

Three such stations were deployed at three VLBI stations (network “Quasar-KVO”) of the Institute of Applied Astronomy RAS and they form collocation nodes together with GLONASS, GPS and DORIS receivers.

| Range | Angular coordinates | Photometry |
|---|---|---|
| S/C orbital altitude: up to 23000 km<br>t of laser pulse ...........200 ps<br>RMSE np ..............5 – 10 mm | Visible star magnitude not weaker than: $12^m$<br>RMSE of measurements.........1 – 2 arc sec.<br>Angular velocities.............. up to 40 arc sec. | Visible star magnitude.....................not weaker than $11^m$<br>RMSE of brightness determination: ......... not greater than $0.2^m$ |

Fig.8 SLR station “Sazhen-TM”

In the foreground is the SLR station far away is 32-m VLBI antenna

Fig.9 Collocation node Badari (Siberia)

At present time, Russian SLR network consists of 10 stations. One more station was brought to operation in Brasilia, Brazil, in June 2014 and immediately started observations of GNSS satellites, including passes in day due to operational calibration of pointing system by daytime stars.

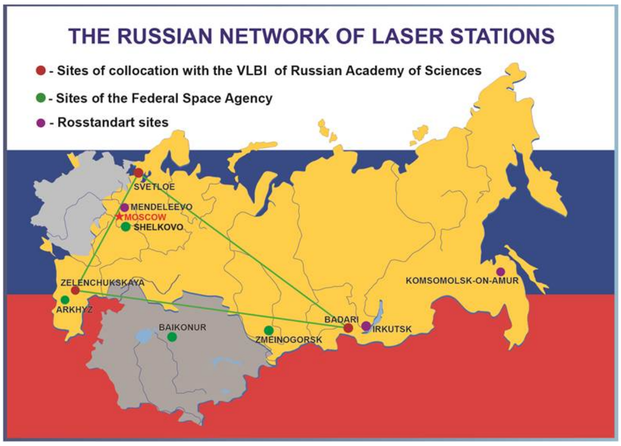


Fig.10 The Russian network of SLR statio (2014)

## LRR arrays and laser satellites

All mentioned stations work with domestic and foreign satellites with retroreflector systems. The biggest number of measurements is with “Glonass” S/C, 24 satellites of the system are equipped with retroreflectors with constantly improving quality.


Fig.11 Key SCs with retro-reflectors with which worked the Russian network of SLR stations

The most accurate laser S/C was glass satellite “BLITS” (with zero signature and target error less than 0.1 mm). It successfully worked at the orbit with altitude of 832 km for 40 months but collided with space debris elements and failed. Development of the next generation satellite “BLITS-M” with better ballistic coefficient and effective scattering area is being finalized now. It is planned to be launched in an orbit above 1500 km in 2016-2017.
The tables (Fig.12 shows data about laser retroreflector systems designed by RPC PSI for Russian and foreign spacecraft).

| SC | Height of Orbit, km | Year of launch | Number of SC | Number of CCRs | Array dimension, mm |
|---|---|---|---|---|---|
| Salyut – 4 (Russia) | 350 | 1975 | 1 | 42 | 184x168x47 |
| Cicada – 11, 13 (Russia) | 1000 | 1976 | 2 | 280 | 235x145x110 |
| Meteor – 1 (Russia) | 950 | 1976 | 2 | 70 | ∅585x210 |
| Molniya -1C (Russia) | 36000 | 1974 | 1 | 70 | 504x318x510 |
| Raduga (Russia) | 36000 | 1976 | 2 | 50 | 306x255x248 |
| GEOIK (Russia) | 1500 | 1981 - 1990 | 11 | 692 | ∅ex1960-∅in1410 |
| GLONASS (Russia) | 19100 | 1982 - 2000 | >50 | 396 | 1330x1010 |
| ETALON 1, 2 (Russia) | 19100 | 1989 | 2 | 2142 | ∅1294 |
| RESURS – O (Russia) | 620 | 1992 | 1 | 2 | 200x160x90 |
| METEOR – 2 (Russia) | 950 | 1993 | 1 | 3 | 190x66x96 |
| METEOR –3 (Russia – Germany) | 1200 | 1994 | 1 | 24 | ∅280x100 |
| Zeya (Russia) | 475 | 1997 | 1 | 20 | ∅968 |
| GLONASS (Russia) | 19100 | 2000 - 2005 | 11 | 132 | ∅ex660-∅in380 |
| METEOR-3M-1(Russia) | 1020 | 2002 | 1 | 1 sph. ∅60mm | ∅88x64 |
| LARETS (Russia) | 690 | 2003 | 1 | 60 | ∅215 |
| Mozhaets (Russia) | 690 | 2003 | 1 | 6 | ∅115x46 |
| GLONASS-M (Russia) | 19100 | 2003 –for now | 45 | 112 | 511x311 |
| BLITS (Russia) | 832 | 2009 | 1 | Autonom.sph. | ∅170 |
| GEO-IK (Russia) | 1000 | failed | 1 | 30 | ∅300x96.5 |
| Radioastron (Russia) | 500-350000 | 2011 | 1 | 100 | 500x406x80 |
| GLONASS-K (Russia) | 19100 | 2011, 2014 | 2 | 123 | ∅ex626-∅in340 |

| SC | Height of orbit, km | Year of launch | Number of SC | Number of CCRs | Array dimensions, mm |
|---|---|---|---|---|---|
| GPS - 35, - 36 (USA) | 20 150 | 1993, 1994 | 2 | 32 | 239x194x50 |
| GFZ-1 (Germany) | 400 | 1995 | 1 | 60 | ∅215 |
| WESTPAC (Australia) | 835 | 1998 | 1 | 60 | ∅245 |
| REFLECTOR (Russia -USA) | 1 020 | 2002 | 1 | 32 | 1445x620x560 |
| GIOVE-A (ESA) | 23 916 | 2006 | 1 | 76 | 308x408x42 |
| GIOVE-B (ESA) | 23 916 | 2008 | 1 | 67 | 305x305x42 |
| GOCE (ESA) | 295 | 2009 | 1 | 7 | ∅125x57 |
| Proba-2 (ESA) | 757 | 2009 | 1 | 7 | ∅114x51 |
| CrioSat 1 (ESA) | 720 | 2005 | 1 | 7 | ∅114x51 |
| CrioSat 2 (ESA) | 720 | 2010 | 1 | 7 | ∅114x51 |
| Proba-V (ESA) | 820 | 2011 | 1 | 7 | ∅114x51 |
| Sentinel-3 (ESA) | 718,5 | 2015 | 3 | 7 | ∅114x51 |
| Galileo (ESA) | 23 222 | | 22 | 60 | 350x253x48,5 |

Fig. 12 Total 147 Russian SC and 47 foreign SC are equipped with laser retroreflectors

**Innovative laser development**

In 2012, the authors proved and started implementation of the “Laser GLONASS” concept based on use of laser counter-measurements of pseudorange in the lines “satellite-satellite” and joint measurements of pseudorange and range in the lines “satellite-ground” for improvement of accuracy of time and coordinate support for “GLONASS” S/C, including, among other goals, GLONASS competitiveness improvement.

The concept is aimed, first of all, at lowering the error of synching of time scales of “GLONASS” onboard frequency standards among themselves and between them and central system synchronizer on the ground. These errors are the main ones in the modern GNSS and depend on on-board frequency standards instability parameters. Pseudorange is a result of work of a one-way laser ranger with “Start” and “Stop” signals registered in spread over large distances time scales. For the line “ground-satellite”, scales difference is equal to difference of laser pseudorange and laser range divided by the speed of light. For the line “satellite - satellite”, half-sum of pseudoranges is equal to the distance between them, and half-difference divided by the speed of light is equal to difference of these two S/C time scales.

Space experiments (*first work of time transfer for GNSS satellite*) performed on 3 “GLONASS-M” S/C confirmed subnanosecond accuracy of determination of difference in time scales between space and ground standards of time and frequency (Fig.13).

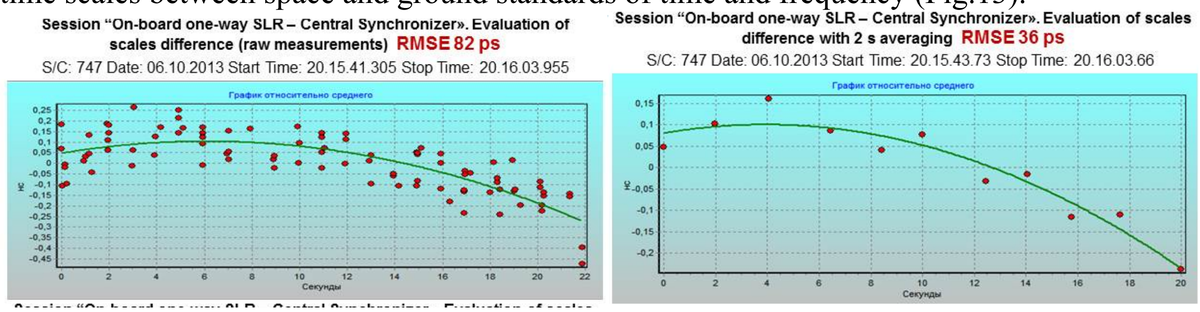


Fig.13 Evaluation of time scales difference between S/C “Glonass-M” # 747 and GLONASS central synchronizer.

One can define calibration data with approximately this error using:
- difference between time scales of each S/C and GLONASS central synchronizer;

- difference between time scales of the central synchronizer and remote time and frequency standards (time transfer to remote sites);
- difference of time scales between S/C with onboard laser terminals that provide measurements and exchange of pseudoranges with all S/C in the global navigation system constellation.

For high-accuracy civilian navigation of GNSS “GLONASS” using PPP (Precise Point Positioning), it is necessary to create a global network of one-way radio stations with improved accuracy characteristics for calculation of high-accuracy ephemeris-time information in real time. For geodetic support and metrological check of accuracy of ephemeris-time information broadcasted by navigation S/C, it is necessary to have a global network of precise SLR stations with millimeter level of accuracy.

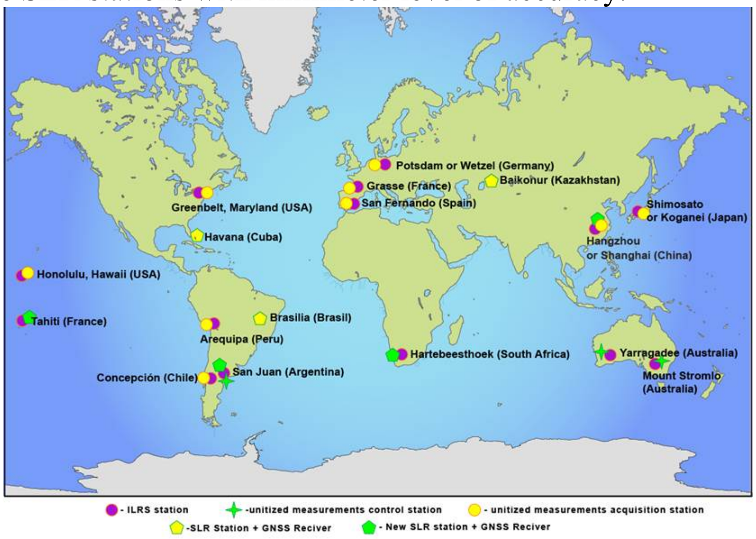

Fig.14 Variant of PPP network with using SLR stations

Development of such SLR station “Tochka” (Fig.15) was started in 2013, with scheduled delivery of a test model in 2015 for solution of a number of problems of laser ranging in GLONASS fundamental segment. The station will make round-the-clock precise (sub-millimeter) laser range measurements using on-board retroreflector arrays and pseudorange measurements (with onboard photoreceiver module) with 25 ps error, as well as measurements of differences between time scales of onboard and ground frequency standards with the accuracy of 50 ps.

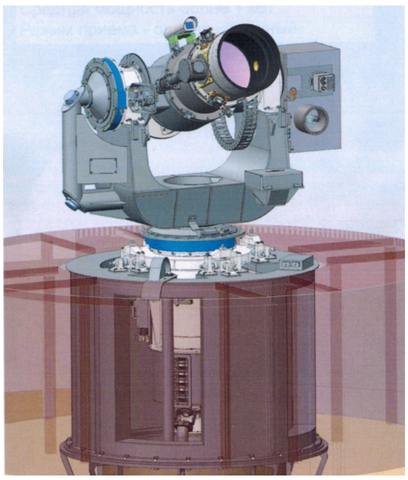
Fig.15 Submillimeter SLR system “Tochka”

Analysis shows that accuracy requirements to instruments necessary for solution of the above mentioned problems of improvement of global navigation accuracy are the same as the instruments necessary for achievement of goals of the global geodetic system GGOS with millimeter accuracy, which is an important synergy factor for accelerated expansion of the global network of SLR stations, radio stations and their collocation in the interest of the both systems.

A direction of satellite laser ranging using diffusive-reflective surfaces of S/C without retroreflectors was developing starting 2005 in the interests of space objects and space debris monitoring in parallel with SLR of retroreflector-equipped S/C. In 2010 there was completed development and start operation of the Laser Optical Ranger of the System for Monitoring of Space (LOR SMS) at Northern Caucasus. This is one of the world's most powerful solid-state laser rangers with energy potential that is at least five orders of magnitude higher than one of a regular SLR station working with retroreflectors. This ranger can work at lunar distances with a panel of retroreflectors, which was confirmed during laser ranging of radio astronomy satellite "Radioastron" equipped with "GLONASS" S/C – type laser reflector array at distances up to 330,000 km.

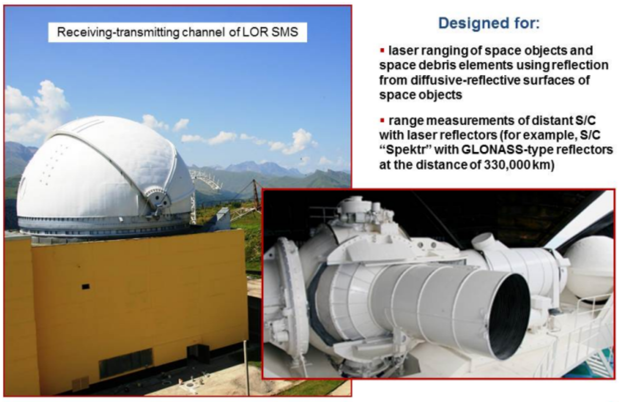


Fig.16 Receiving the transmitted channel of LOR SMS

Development of the lunar laser ranger based on 3.12m telescope at Altai optical laser center, to obtain range measurement with a precision of 3 mm for precise calculation of lunar ephemeris in the interests of GNSS "GLONASS", diffraction imagery of space objects and space debris elements and determination of their orbits using angular and range measurements was started in 2014.

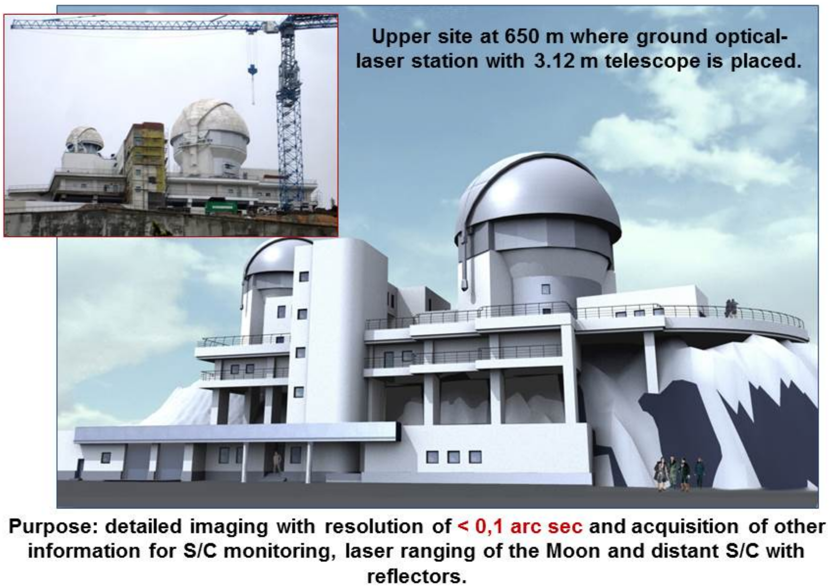


Fig.17 The second phase of the Altai optical laser center (project). At the top is panorama construction.