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Current state of high-accuracy laser ranging

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Contents

Abstract. Laser ranging currently provides millimeter accuracy at megameter scales, but even higher accuracy will be required in the near future. Factors limiting the accuracy are variations in the refractive index of Earth's atmosphere and the structure of light-reflecting targets. In this paper, we briefly outline strategies to overcome these limitations and review the progress in deploying Russia's satellite laser ranging network over recent decades. Some prospects for further progress in this field are also discussed.

Keywords: satellite laser ranging, retroreflector, target error

1. Introduction

High-precision laser ranging is currently used in solving a large number of problems, but among these problems there are two outstanding ones due to their constant relevance and a broad range of applications: determining the coordinates of fixed points on Earth's surface (geodesy) and measuring instantaneous coordinates and motion parameters of dynamical objects (navigation). In the 20th century, the mechanical devices for these measurements — the measuring tape or a wheel-based device — were replaced by devices measuring the propagation time of radio frequency (RF) and optical electromagnetic waves (the propagation time of acoustic waves is also used for underwater and underground measurements).

For these problems, the optical range has both advantages and disadvantages in comparison with the RF range: the latter is weather independent and in some cases allows over-horizon measurements (by using radio wave diffraction), but the accuracy of the RF range is affected by the electromagnetic field distortions caused by local objects and environmental factors (the atmosphere and the ionosphere), which determine the propagation speed of RF fields.

In the optical range, these precision-limiting factors turn out to be weaker, but the losses in the air become higher (especially due to scattering on aerosols [1] [1] and the influence of the solar radiation background, which often leads to high noise in measurements).

Therefore, it is reasonable to combine features of both ranges. The optical methods, which are currently typically associated with laser ranging, are used to calibrate and compare the RF systems.

In the middle of the 20th century, high-precision ranging by measuring the propagation time of electromagnetic waves was mostly used for ground geodetic applications. For these tasks, accuracy is more important than operability (except in military applications), and therefore optical (from the early 1960s, laser) rangefinders became more popular. The distances measured did not usually exceed several dozen kilometers, and the method used most frequently was phase ranging (measurement of the phase shift of a modulating signal applied to a propagating light beam).

The development of cosmic navigation geodetic systems led to the implementation of this technology in ground navigation networks, and the laser ranging used in these applications was called satellite laser ranging (SLR). Because widespread satellite navigation is based on geodesy, requirements for the precision of geodetic navigation systems are increasing rapidly, and laser ranging as a reference calibrating method must meet the strictest requirements.

In the 1960–1970s, several decimeters was assumed to be a small ranging error, but since the 2000s, the attainability of a ± 1 mm precision is being discussed.

To solve these kinds of problems globally, the International Laser Ranging Service (ILRS) has been established [3]. The Russian Federation joined the ILRS at the beginning of the 1990s. Currently, the ILRS supports the operation of more than 50 stations around the world and there are several dozen stations under construction or reconstruction.

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[1] On the contrary, during propagation in an aqueous medium (especially for the blue–green spectral band), the losses become smaller than in the RF band [2]. Therefore, optical ranging (as well as data transmission) finds its application in underwater operations.

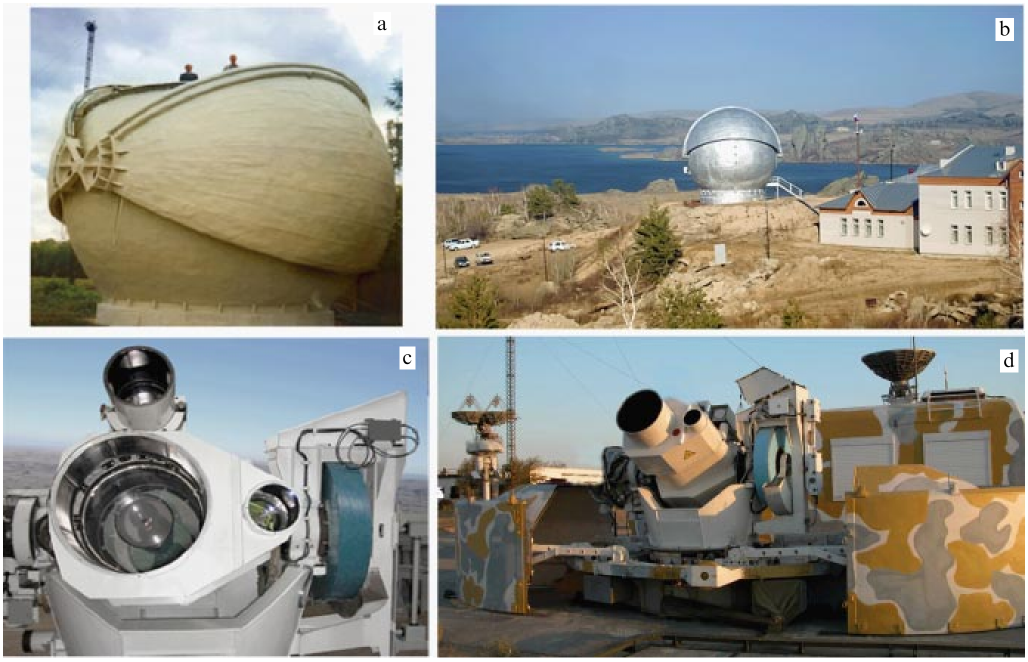

Figure 1. Satellite laser rangefinders of Sazhen-T series designed for GLONASS-M second-generation space devices. (a) SLR station in Schelkovo, launched in 2000. (b) SLR system of the Altay Optical Laser Center launched in 2006. (c) Telescope for trajectory measurements at the Altay Optical Laser Center. (d) Mobile SLR station Sazhen-TOS launched at the Baikonur Cosmodrome in 2006.

We note that such a network is optimal when it is distributed over Earth's surface evenly, and in the 1990s, the ILRS had grave concerns: the territory of the largest country in the world, Russia, was very poorly covered with SLR stations (in Russian, they are often referred to as quantum optical stations, KOSs). However, nowadays, Russia is a leader with regard to that parameter: there are 20 operating stations on the Russian territory, and there will be 29 by 2020. Moreover, Russia is involved in increasing the concentration of the SLR network in the southern hemisphere, which has less coverage than the northern hemisphere (two of the Russian stations, in Brazil and the Republic of South Africa, are already successfully operating).

The SLR station design is also changing: the stations are becoming more compact and more precise. In the early 1970s, the first Russian laser stations contained optical devices based on 1.5-meter searchlight mirrors (the SKOL-2 laser locator had four mirrors on a common rotating base), while the current industrial laser station, Sazhen-TM, has a dual optical system with a 25 cm mirror diameter providing the same operational range and an order of magnitude higher accuracy.

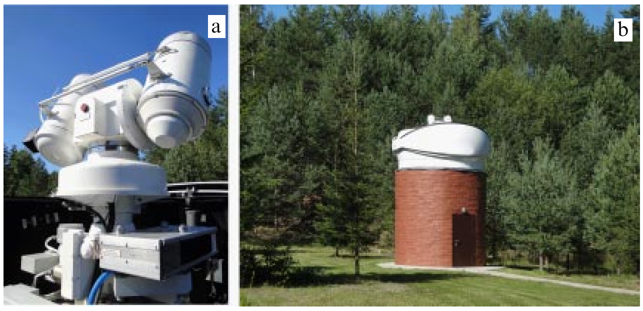

Figure 2. Mass-produced compact SLR station Sazhen-TM (developed in 2005), which realizes the method of high-frequency laser ranging: (a) general view of the station, (b) Sazhen-TM in housing (Leningrad region, Svetloye). Pulse repetition rate is 300 Hz, power is 0.75 W. Range: the orbit height is up to 23,000 km, the laser pulse length is 200 ps, the root-mean square (rms) in standard pulses (at the 'normal point') is 3–8 mm. Angular coordinates: the apparent magnitude is not less than 12^{m}, the measurement rms is 1–2 arcsec, the angular velocity is up to 49 arcsec. Photometry: the apparent magnitude is not less than 11^{m}, the photometry rms is not larger than 2^{m}.

2. Types and characteristics of laser ranging stations

Our facility at the Research and Production Corporation Precision Systems and Instruments (RPC PSI) produces laser ranging stations of various types. Various stations currently operating are shown in Figs 1 and 2, and their locations in Russia and neighboring territories are shown in Fig. 3.

The world's highest precision (also available with our stations) is approximately 0.5 cm. At the special international meeting held in Eastbourne (Great Britain) in 2005, called 'Towards 1 mm Accuracy' [4], it was stated that the precision is mainly limited by two factors: difficulty in introducing accurate corrections for the atmosphere refractive index along the laser beam propagation path and the so-called target error. We consider these factors in more detail.

The refractive index of air close to Earth's surface is ~ 1.0003 [5], which results in a time delay of the propagating signal from ~ 3 m to ~ 10 m (in distance units), depending on the 'elevation angle' (the angle between the beam line and the horizon plane). Operation at small elevation angles, for which the delay is more than 10 m, is undesirable. The refractive index of air depends on its temperature, pressure, and humidity, and these factors can be measured only at the station location. Currently, it is possible to use a model of the atmosphere and to take all the details of the distribution of these parameters along the beam path into account, which in

Figure 3. (Color online.) Russian network of SLR stations.

the best case results in an error of several millimeters (in distance units), although the analysis of local conditions, together with improvements in the general model of the atmosphere, may allow gradually increasing the accuracy.

Theoretically, there is the following strategy of solving this problem: simultaneous distance measurement using lasers with two distant wavelengths (for example, in the visible and infrared spectral bands). By using the dispersion relation (the refractive index dependence on the wavelength) one can in principle obtain the value of the signal delay in the atmosphere without measuring the temperature, pressure, or humidity of the air along the beam path. However, it was shown that in order to achieve a 1 mm precision in distance measurements, the time delay between the propagation times of these waves must be measured with an accuracy better than ± 0.5 ps [5] (that is, ± 0.07 mm in distance units), which cannot be realized yet due to a number of technological problems.

3. Satellite targets

Another serious limiting factor for the precision is the target error. Almost all satellite targets for high-frequency geodetic and geophysical measurements are metal spheres covered with a large number of retroreflectors — fused silica cube corner reflectors (most of these satellite targets and retroreflectors are manufactured by RPC PSI) (Table 1 and Fig. 4). The diameter of these spherical devices ranges 0.23 to 2.15 m and the number of retroreflectors on each device is from 20 to 2142.

Due to simultaneous reflection of the laser pulse from several retroreflectors located at different distances from the station and due to the inevitable dispersion of the effective reflecting areas of these reflectors, an error occurs, which for large spherical satellite targets reaches several centimeters (Fig. 5 and Table 2).

Already in 1990, RPC PSI developed a special SLR target, WESTPAC (Western Pacific Satellite) (see Fig. 4), in order to solve specific high-precision geodynamic problems (specifically, for the Japanese Keystone project that predicts earthquakes and tsunamis based on the observations of weak movements of Earth's crust). At each time instant, the laser signal is reflected from only one retroreflector, which is achieved by limiting its angular field with special blends. This allowed decreasing the mean value of the target error for this satellite to 0.5 mm, but it also caused some difficulties during the observation: there were pauses between series of reflections from different retroreflectors. The idea was to average the experimental results by triggering the spinning motion of the satellite during its launch into orbit, but the rotation gradually slowed down due to the currents induced in the metal housing by Earth's magnetic field (we note that this disadvantage is more or less relevant for all metallic spherical satellite targets).

To radically overcome the difficulties associated with the target error, we proposed, manufactured, and launched into space a satellite target of a completely new type, BLITS (Ball Lens In The Space). This satellite target is a glass ball, which uses the Luneburg lens principle [6, 7] and focuses an incident radiation beam with a flat front on the opposite surface of the lens (Fig. 6). By applying a reflective coating on the hemisphere and bringing it to rotational motion around the axis in the plane between the reflective an transparent surfaces, a reflected signal can be produced as a series of periodically repeating pulses. Such a satellite does not contain any metallic parts where eddy currents can appear, and hence its rotation remains constant during its entire service in space.

Such a satellite is almost a 'point-like' target that does not disturb the shape of the reflected pulse, and the effective reflection point does not oscillate with respect to the satellite

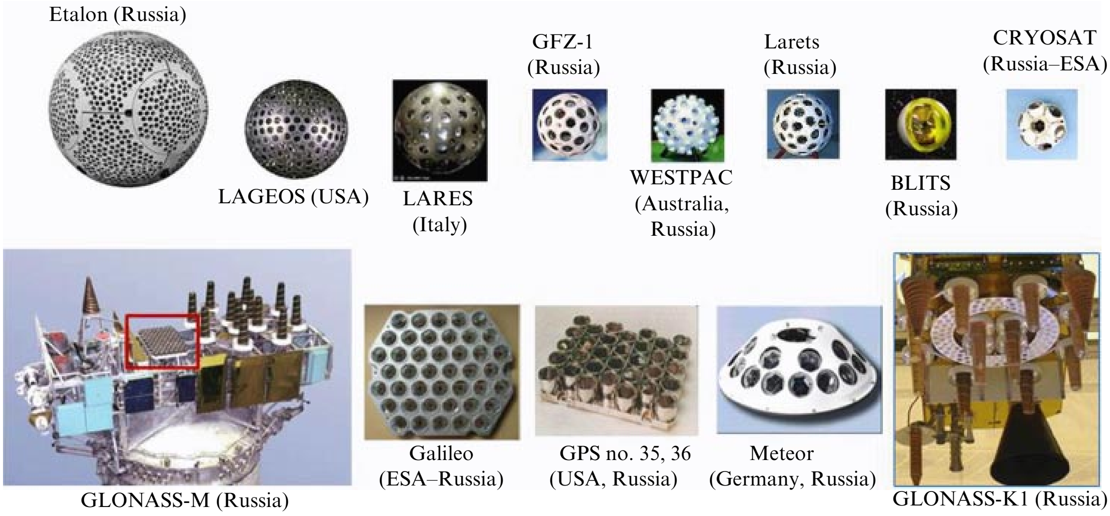

Figure 4. Russian and foreign retroreflecting systems and satellites.

Table 1. Laser retroreflecting system developed at RPC PSI for Russian spacecraft.*

Type of spacecraft (S/C)	Orbit height, km	Launch year	Number of S/C	Number of retroreflectors on S/C	Retroreflecting system size, mm
Salut-4	350	1975	1	42	184 × 168 × 47
Tsikada-11, -13	1,000	1976	2	280	235 × 145 × 110
Meteor-1	950	1976	2	70	∅ 585 × 210
Molniya-1S	36,000	1974	1	70	504 × 318 × 510
Raduga	36,000	1976	2	50	306 × 255 × 248
GEO-IK	1,500	from 1981 till 1990	11	692	$\varnothing_1 1960 - \varnothing_2 1410$ (ring zone)
GLONASS	19,100	from 1981 till 2000	> 50	396	1330 × 1010
Etalon-1, -2	19,100	1989	2	2142	∅ 1294
Resurs-0	620	1992	1	2	200 × 160 × 90
Meteor-2	950	1993	1	3	196 × 66 × 96
Meteor-3 **	1,200	1994	1	24	∅ 280 × 100
Zeya	475	1997	1	20	∅ 968
GLONASS	19,100	from 2000 till 2005	11	132	$\varnothing_1 660 \times \varnothing_2 380$
Meteor-3M-1	1,020	2002	1	1 sphere ∅ 60 mm	∅ 88 × 64
Larets	690	2003	1	60	∅ 215
Mozhaets	690	2003	1	6	∅ 115 × 46
GLONASS-M	19,100	since 2003 till now	45	112	511 × 311
BLITS 2009	832	2009	1	Autonomous sphere	∅ 170
GEO-IK-2	1,000	2011, Unsuccessful launch	1	30	∅ 300 × 96.5
Spektr-R	Elliptical (apogee up to 350,000)	2011	1	100	500 × 406 × 80
GLONASS-K	19,100	2011	1	123	$\varnothing_1 626 \times \varnothing_2 340$ (ring zone)

* Total number of retroreflector-equipped spacecraft is 148.
** Russia–Germany

center of mass. The temperature variations in the glass refractive index lead to ranging errors of less than 0.1 mm.

This satellite was launched into orbit at the height of 835 km, and it was successfully observed by all stations of the international SLR network from the beginning of 2009 till the end of 2013. The BLITS satellite was a prototype for the new BLITS-M satellite with somewhat greater size and mass. This satellite is currently being prepared for launch into a 1500 km

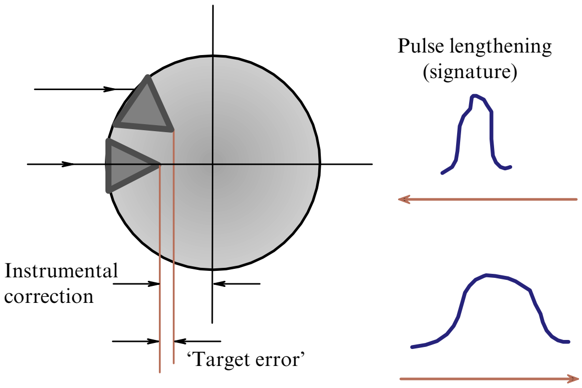

Figure 5. Occurrence of the target error.

Table 2. Retroreflecting system parameters.

Retroreflecting system	Orbit height, km	'Target error'*, mm	Pulse lengthening (signature)*
Ajisai (Japan)	1,400	50	Yes
Etalon	19,100	40	Yes
GLONASS	19,100	25	Yes
LAGEOS (USA)	5,800	10	Yes
Larets	690	2.0	Yes
WESTPAC	835	0.5	No
BLITS	835	0.1–0.3	No

* See Fig. 5.

high orbit, where there is almost no influence of the atmosphere on orbit stability. This would allow effectively using this spacecraft for geophysical and geodetic measurements with a previously unavailable precision.

An important addition to the long-range systems considered above is the recently developed one-way satellite LRS [8], which is designed for laser pulse transmission from a ground station to receivers on the Global Navigation Satellite System (GLONASS) spacecraft. The received pulses can be linked to the onboard time scale of the corresponding spacecraft (Fig. 7). By linking high-precision 'clocks' of the ground laser station to this time, onboard time scales of GLONASS devices can be compared with the ground reference signal and significantly improve the onboard GLONASS time synchronization, which, in turn, improves the precision of the corresponding navigation geodetic measurements thanks to low errors of the laser link.

In the nearest future, all new ground stations will be equipped with this system. Good coverage of Earth's surface with a network of stations will significantly improve the precision of GLONASS and give it an advantage with respect to other global satellite geodetic navigation systems. Moreover, GLONASS will be even more greatly improved by equipping all new spacecraft with laser links of the inter-satellite laser navigation and communication system (ISLNCS) for the fast exchange of data on the time delays on these devices (Fig. 8). The ISLNCS apparatuses are basically a combination of a one-way rangefinder and a low-information connection link.

4. Future prospects of laser ranging

What are the future prospects for high-precision SLR after equipping the measurement network with new Sazhen-K and Sazhen-L industrially producible stations (Fig. 9) [9] with a one-way SLR system and the potential to reach an error of 1–2 mm, and after significantly broadening the high-precision station network? What are the ideas, plans, and potential of our facility for the coming years?

First of all, we plan to launch the second stage of the Altay Optical Laser Center[2] with a 3.12 m diameter telescope (Fig. 10) and a laser rangefinder, which will efficiently measure the distances to retroreflectors installed on the Moon with millimeter precision.

We note that during the last three years we have already been performing measurements at distances comparable to the distance to the Moon. This was done by using a retroreflecting panel installed on the Radioastron spacecraft with an elongated elliptical orbit and an apogee of almost 350,000 km. However, the precision of the devices used was about 1 dm, which suffices for the problems of this specific cosmic mission but not for solving fundamental problems regarding studies of the Moon and the Moon–Earth system. It is important to note that our Earth geodesy and navigation measurements are performed in the system whose center of masses is located inside the bound Earth–Moon system, and therefore even 'terra firma' oscillates depending on the Moon's position, not to mention the ocean water level.

Lunar Laser Ranging (LLR) is currently performed by only three stations (two in the USA and one in France), which have the corresponding equipment: high-power short-pulse lasers and large telescope receivers. In the nearest future, our

[2] The first stage of this measurement and research center has been operating for more than 15 years already.

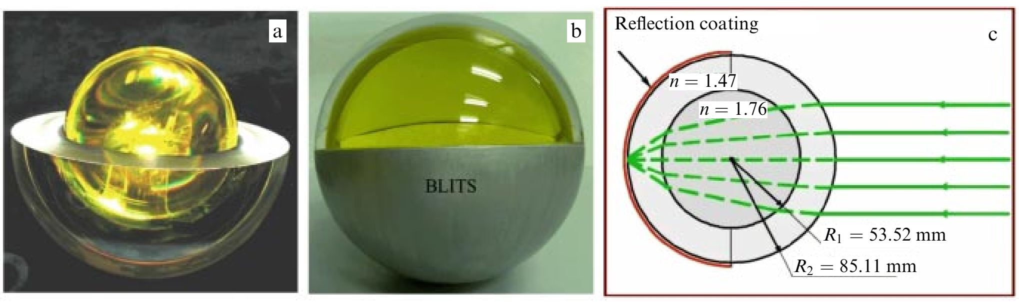

Figure 6. Spherical glass satellite BLITS: (a) disassembled; (b) flight model; (c) schematic of the device. Main parameters of BLITS (BLITS-M): diameter 170 mm (220 mm), mass 7.5 kg (17 kg), orbit height 835 km (1500 km), effective scattering surface 10^5 m^2 (10^6 m^2), target error 100 µm (100 µm).

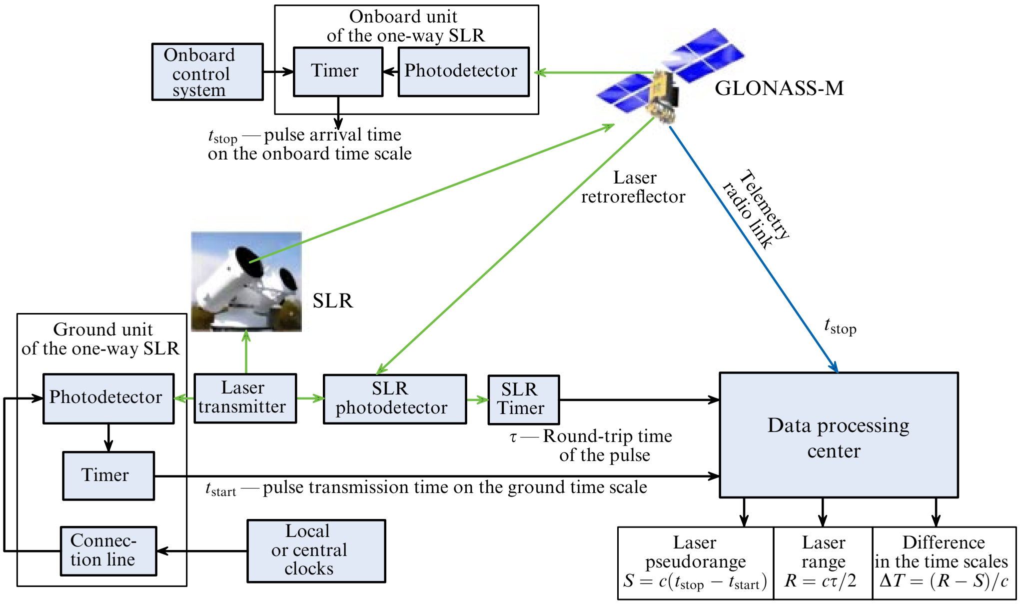

Figure 7. Using a one-way SLR for the synchronization of onboard and ground time scales.

Figure 8. Inter-satellite laser navigation and communication system. ISLNCS unit for GLONASS-M 752, 753.

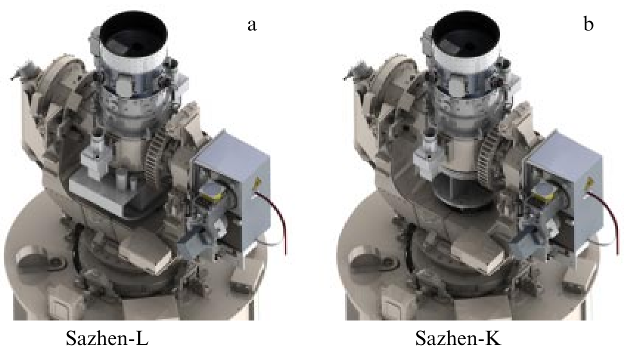

Figure 9. High-precision laser systems for range measurements and time transmission: (a) SLR Sazhen -L, (b) SLR Sazhen-K.

Figure 10. General view of the construction site for the second stage of the Altay Optical Laser Center with the TI (Telescope Informational). The diameter of the mirror will be 3.12 m.

station in Altay will be added to this list. The timing of this project is related to new space missions during which new retroreflecting systems, including those manufactured at our facility, will be delivered to the Moon.

Currently, there are three retroreflecting panels on the Moon, which were delivered there by the astronauts of the Apollo-11, Apollo-14, and Apollo-15 missions, and two smaller panels installed on the Soviet Lunokhod-1 and Lunokhod-2 devices. However, all these systems were delivered to the Moon more than 40 years ago, and their efficiency has decreased due to natural reasons (dusting or erosion of the surface and possibly radiation degradation)

5. Conclusions

To conclude, we share some insights into the future of laser ranging stations and networks.

Today, there are technologies already developed and experimentally verified that allow creating portable ranging systems with the same (and even better) precision and range characteristics as at the currently operating and produced stationary systems. Instead of a dome or other stationary buildings, these stations would require only a casing or a cover, just as for portable geodetic devices, which would provide new conditions for the development of measurement networks.

This would also greatly reduce the time needed for high-precision measurements due to the high repetition rate of laser pulses and hence higher radiation mean power. Higher informational efficiency is extremely important due to the rapidly increasing number of target spacecraft with retro-reflectors.

Extending the ground laser station network not only gives new opportunities but also brings up or, more precisely, aggravates some problems, especially those associated with operation safety.

Measurements in the visible range (almost all stations use lasers with 532 nm wavelength lasers, green light) are performed at the high laser powers needed for large-distance measurements. This creates a danger for human eyes, which can accidentally appear on the beam path or on the path of the beam reflected from mirror surfaces. To prevent such situations, the stations are equipped with warning systems monitoring the motion of aircraft, in which pilots and/or passengers might be harmed by the laser radiation. In addition, it is forbidden to work at small elevation angles, when a beam almost parallel to Earth's surface can hit the windows of ground buildings or eyes of the people standing on high ground. Extension of the station network will increase the chance of such dangerous situations.

For this reason, the transfer of laser stations into the 'safe' infrared band is being discussed: at wavelengths longer than 1.3 μm, the radiation is not transmitted through the eyeball (glass-like material) and does not reach the retina, which contains sensitive elements of the eye [10]. A transition to the $\sim$ 1.55 μm wavelength, which can be efficiently generated and for which there are sensitive and high-speed detectors, would be the most promising. Such a transition would help create 'safe station generation', which in turn would contribute to the extension of the measurement network.

If laser stations were equipped with transmitters at the 1.55 μm radiation wavelength and at the same time visible band transmitters were kept, it would be possible to apply the 'refractometric' method mentioned above for correcting the pulse delay time in the atmosphere. This method is based on the dispersion relation for air and requires simultaneous measurement at two wavelengths (for example, at 0.53 and 1.55 μm). Currently, there are already available receivers that can efficiently operate at these wavelengths without the necessity of using different detectors. This allows unifying the optical systems of such rangefinders and makes it easier to reach the highest precision for the measurement of the time delay between the received pulses with these wavelengths. This would solve another (the last?) problem on the way towards submillimeter precision of satellite laser ranging.

The next step on this path, as we believe, would be the 'transfer' of measuring devices (laser ranging stations) from Earth to spacecraft; on Earth's surface one would then only need to install retroreflectors and small laser beacons to guide the onboard rangefinder. The onboard laser station would of course operate not only with the ground stations but also with spacecraft equipped with retroreflectors, and these connections would not be disturbed by meteorological conditions.

We note that the instantaneous coordinates of an onboard measurement station situated in a high enough orbit can be measured with a very high precision (the coordinates of ground laser stations are currently defined by the link with LAGEOS-type (Laser Geodynamics Satellite) spacecraft with an orbit height of about 6000 km).[3]

Essential simplification, miniaturization, and price reduction of ground stations would allow the ground network to quickly become denser, covering hard-to-reach locations (where it is hard to build active laser stations with their infrastructure) and eventually rapidly increasing the efficiency of the high-precision laser ranging network.

Unfortunately, in a short article, it is not possible to mention, even briefly, other multiple applications of high-precision laser ranging, from the most important problems of fundamental science to various practical devices, including consumer ones.

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[3] Interestingly, the installation of ranging devices aboard a spacecraft would also allow increasing the energy budget of the measurement line due to lower divergence of the laser beam, which would not be disturbed by the atmospheric turbulence close to the ground laser station. The efficiency of ground retroreflecting systems would be increased due to stabilization of their operation conditions. It is easier to protect ground retroreflectors from the action of sunlight and thus prevent the degradation of the reflective characteristics due to temperature gradients, etc. Also, because the reflector aperture is usually smaller than the coherence area of the turbulent atmosphere ('fried diameter' [11]), the wave front will be linearly inverted after reflection, and atmospheric turbulence will be 'frozen' during the round trip of the beam, which would provide nonfluctuating and nondegrading reflected beams.