Lunar Laser Ranging in the Lebedev Physical Institute of the USSR Academy of Sciences

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The Moon was the first cosmic object, distance to which was measured by means of laser ranging. The first experiments in Lunar Laser Ranging (LLR) were accomplished at the McDonald observatory, USA [1].

Simultaneously, in 1962, work towards the construction of LLR equipment started in the Lebedev Physical Institute (LPI; usually abbreviated as 'FIAN' in Russian that stands for Physical institute of the Academy of Sciences), Moscow, by the orders of N.G. Basov, the head of the Laboratory of Quantum Radiophysics, a future Nobel Prize winner (Fig. 1).

Fig. 1. Nikolay Basov

Fig. 2. Yuri Kokurin

First results were obtained by the team of the Crimean Scientific Station (CSS) of the LPI, Katzively, under the supervision of Yu.L. Kokurin (Fig. 2) in collaboration with colleagues from LPI and Crimean Astrophysical Observatory (CrAO) in Nauchny (Fig. 3). The first ranging session took place on September 13, 1963 with the use of created by LPI team ruby laser exploiting the regime of free generation of millisecond pulses with energies in the interval 50—70 J (Fig. 4). Laser impulses were sent and received by the 2.6 m Shajn Mirror Telescope of the Crimean Astrophysical Observatory (Fig. 5). Albategnius, a crater located on the dark side of the Moon, was chosen as a target for laser beam. The measurements allowed reliable detection of the signal reflected from the Moon. The distance to the Moon was measured with the accuracy of 150—300 km [2].

Fig. 3. LLR team near the dome of the 2.6 m Shajn Mirror Telescope in CrAO, Nauchny, 1984

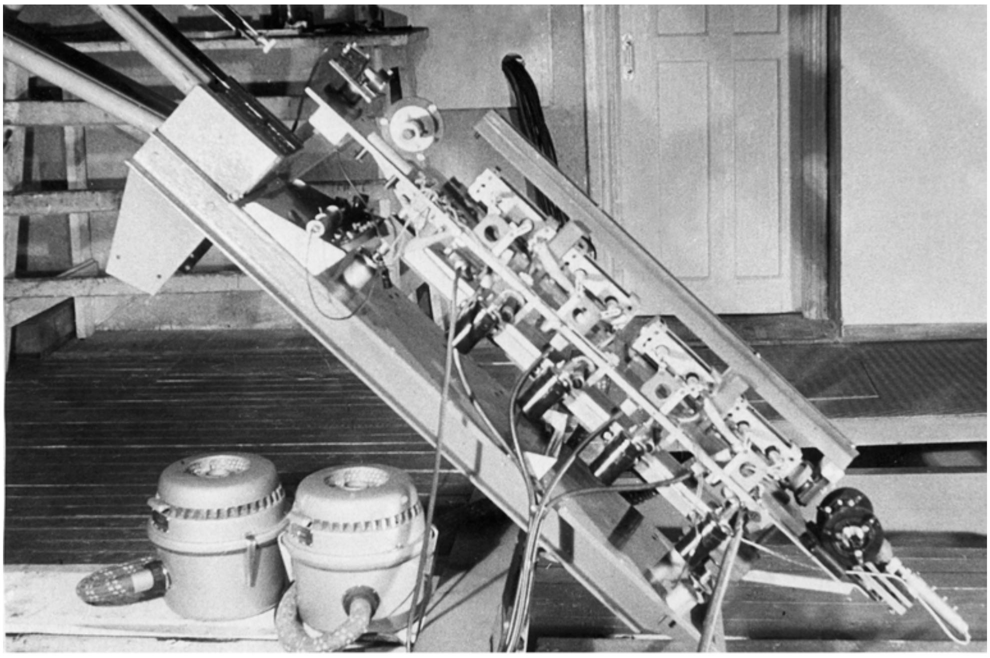

Fig. 4. First ruby laser used for LLR in coudé focus, 1963

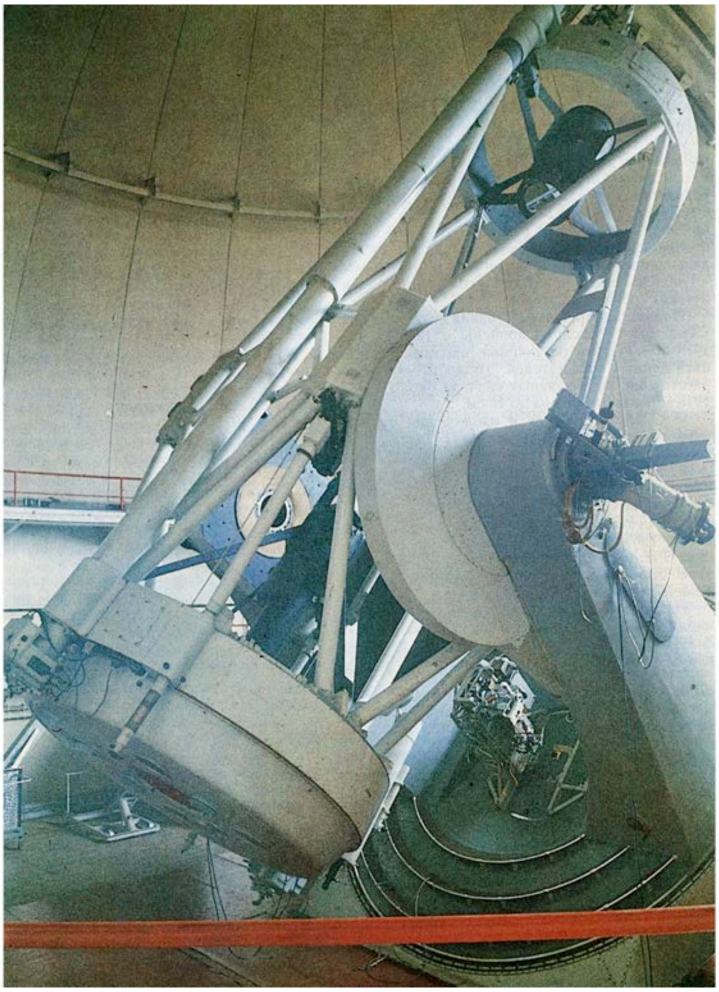

Fig. 5. 2.6 m Shajn Mirror Telescope

In 1965 the same team was the first to use a new laser with Q-switch modulation. This laser generated impulses with a pulse length of 50 ns and energy of 5—7 J. On October 15, 1965 this laser and more advanced equipment complex were used in a successful run of measurements of the distance to the bottom of Flammarion lunar crater. Fig. 6 shows a histogram of the signal detected in this experiment. With the instrumental error of approximately 15 m, the distance was measured with the accuracy of about 200 m due to topographic inequalities and the angle of incidence of the beam onto the bottom of the crater [3].

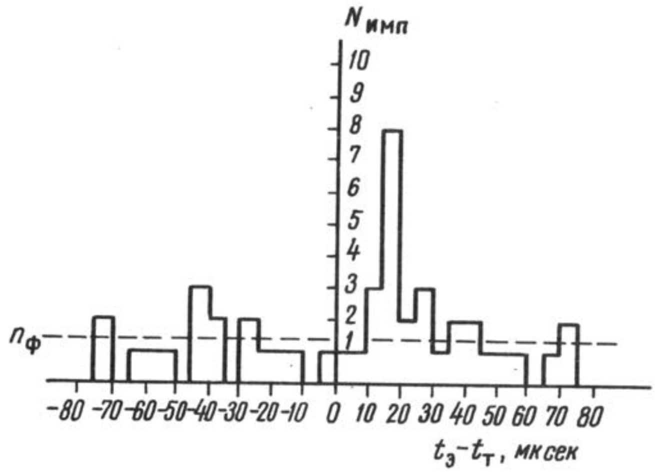

Fig. 6. Abscissa axis: difference between measured and predicted 2-way time of light propagation between the telescope and Flammarion crater on the Moon in microseconds; ordinate axis: number of pulses detected. October 15, 1965

These first experiments have proven the feasibility of the Lunar Laser Ranging but also have shown the constraints on the measurement accuracy caused by the lunar surface relief and oblique incidence of the beam onto the target area. The method of laser ranging has shown evident prospects of its implementation in astrometry, geodesy, geodynamics, geophysics, in the study of relativistic and gravitation effects, etc. provided the accuracy of laser ranging can be substantially improved.

This was made possible due to transportation and installation of corner cube reflectors on the Moon as point-like targets for laser ranging [4]. That is why further efforts in this field had been applied in the LPI in the frame of the program for creation and delivery of “Lunokhod” lunar rovers to the Moon’s surface. Staff of the Crimean Scientific Station of the LPI participated in creation and installation of corner reflectors on the vehicles. On the very first Lunokhod (lost due to launch mishap) hollow coated retroreflectors made by Vavilov State Optical Institute, Leningrad, were installed (Fig. 7), other missions (successful) had French reflectors. Several configurations of laser ranging equipment were built in the CSS for laser observations of these reflectors.

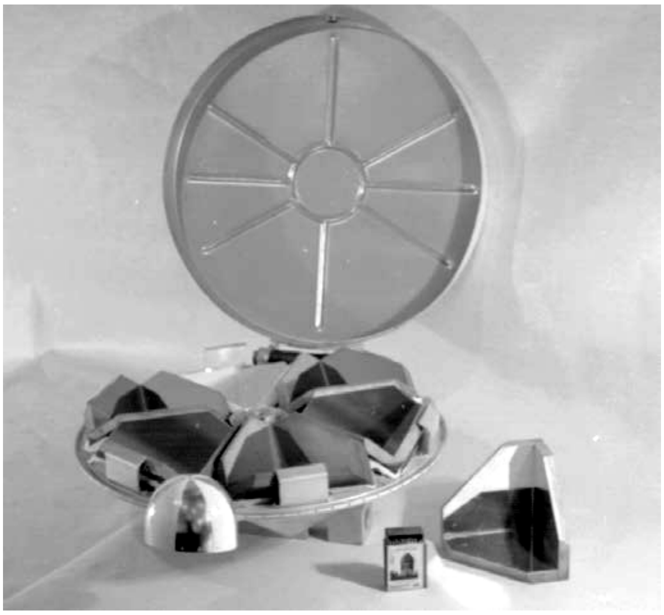

Fig. 7. Corner cube array made by Vavilov State Optical Institute for Lunokhod missions, 1968. A box of matches is for scale

It is well-known that in 1969—1973 five retroreflector packages were placed onto the lunar surface: Apollo-11, Apollo-14 and Apollo-15 (USA), and Lunokhod-1 and Lunokhod-2 (USSR—France) which enabled to measure the distance to the Moon with high accuracy.

In 1969 the program of lunar ranging with the use of Apollo-11 reflector started at the McDonald Observatory. The same year teams of the CSS and CrAO began installation of the new laser transmitter (Fig. 8) and registration complex for LLR observations on the 2.6 m telescope in Nauchny. These operations had been completed by the moment of landing of Lunokhod-1 onto the Moon's surface, and on December 6, 1970 the first results of laser ranging with the use of Lunokhod-1 retroreflector array were obtained with the accuracy of individual measurement ~3 m [5]. Fig. 9 depicts the result of signal accumulation from the Lunokhod-1 array in the time window.

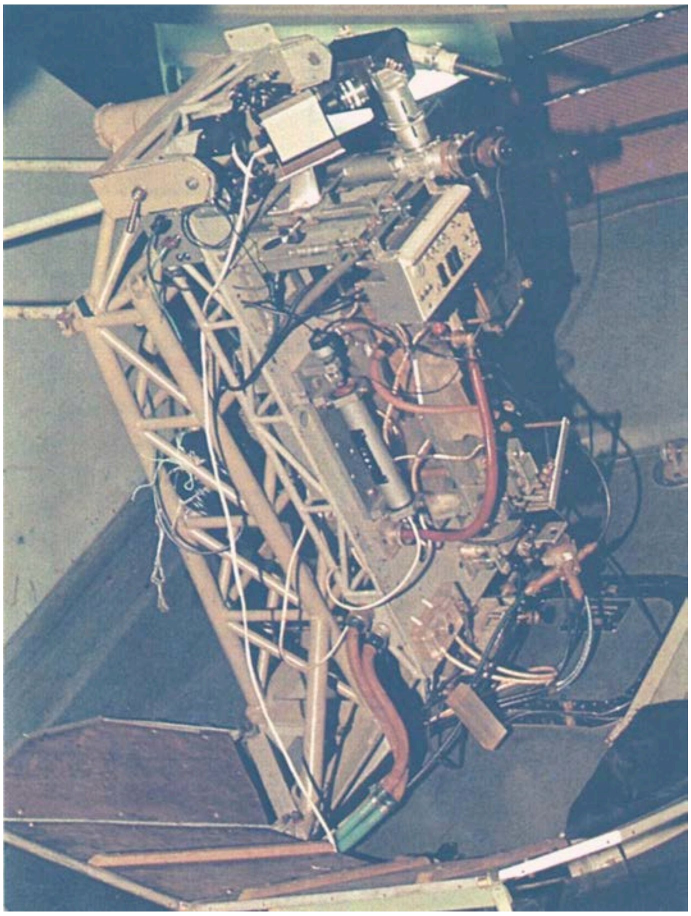

Fig. 8 One of the variants of laser transmitter

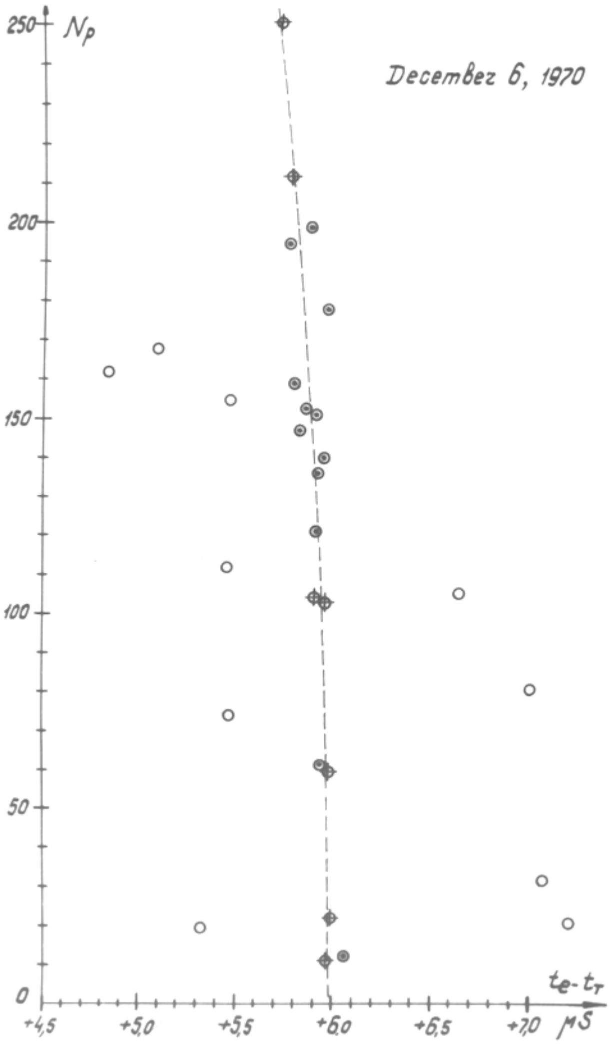

Fig. 9. Echoes from Lunokhod-1

Fig. 10. Laser in the ‘coudésmyth’ focus.

The laser transmitter, as can be seen in Fig. 10, was installed not in the coudé focus of the telescope, as in 1963—1965, but in the combined coudé-Nasmyth focus. In order to modify the telescope in such a way, the secondary mirror was installed as for the Nasmyth focus, while the diagonal mirror was transferred into the position for the coudé focus. This type of focus was called ‘coudésmyth’. Such setup of the laser (in the center of the polar rotating platform and at the shorter focus than coudé, 42.5 m) provided wider field of view, 15 arcminutes (which was necessary for the applied method of offset guidance for tracking of the lunar retroreflectors), and more precise pointing of the telescope. Such mounting of our laser transmitter at the 2.6 m telescope turned out to be the most successful and was used in all subsequent observing sessions.

Cardinal reconstruction of the equipment in the frame of Lunokhod-2 project resulted in creation of the automated complex (Fig. 11) with the accuracy of individual measurement of ±0.9 m, which has been used for regular laser ranging of all lunar retroreflectors since 1973 [6].

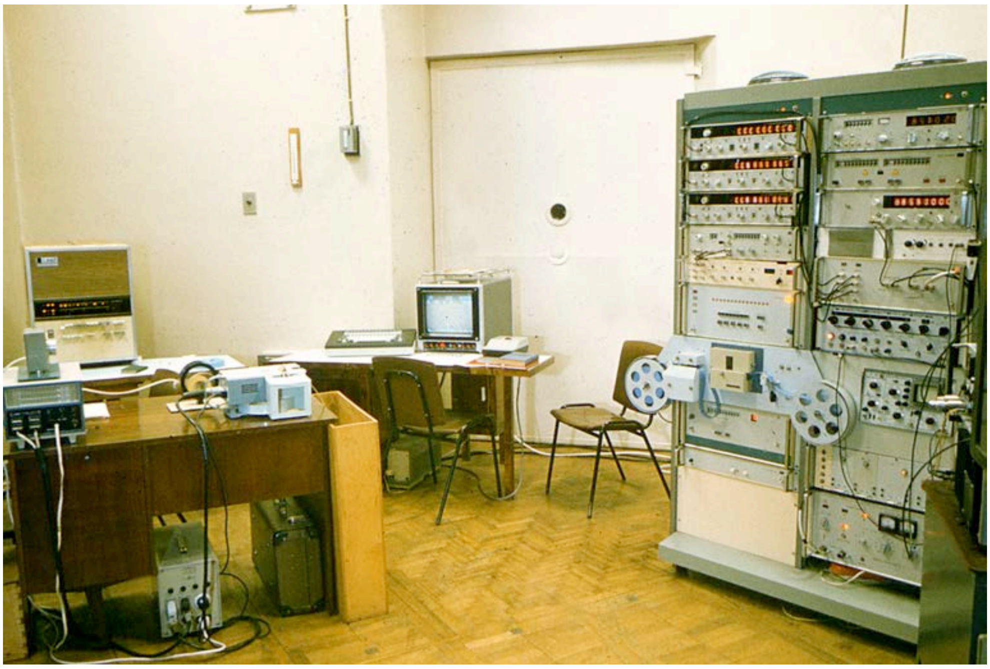

Fig. 11. Automated complex for LLR in Nauchny (last incarnation)

One of the first scientific results of Lunar Laser Ranging obtained in collaboration with the American team was a high-precision measurement of the distance between McDonald Observatory and Nauchny with the accuracy of 0.6 m. That was done independently by O. Calame [7] and S.G. Shubin.

The accuracy of an individual measurement was improved up to 25 cm after installation of a new laser in 1978 [6]. Fig. 12 shows results of signal accumulation during laser ranging to Lunokhod-2 on November 22 (Λ-2) with a new laser and to Appolo-15 retroreflector array on August 26 (Ap-15) with an old one.

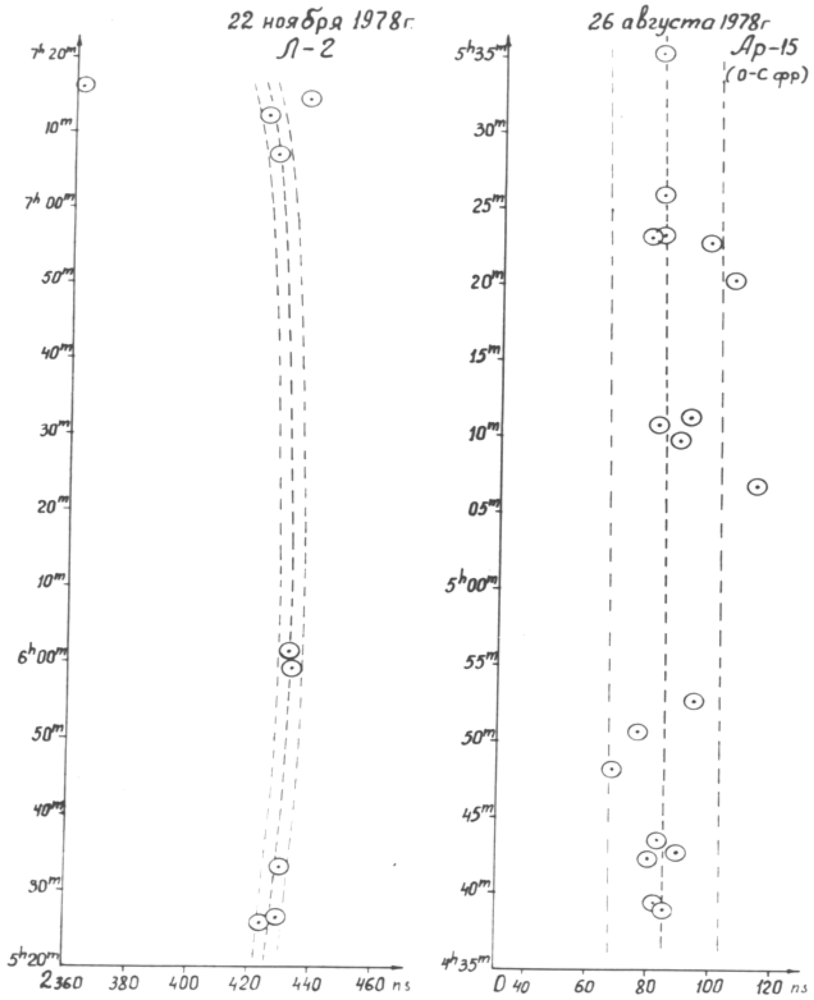

Fig. 12. Echoes from Lunokhod-2 on November 22, 1978 (left) and from Appolo-15 retroreflector array on August 26, 1978 (right).

During the decade 1973—1983 CSS team obtained 1400 individual distance measurements to the Moon (predominantly with the use of Apollo-15 and Lunokhod-2 retroreflectors). All laser-ranging facilities created for this program were composed of the devices and components made in the Soviet Union.

Ephemerides of the Lunar craters, and, later, of the retroreflectors delivered to the Moon were prepared by the team from the Department of the Moon of the Institute of Theoretical Astronomy in Leningrad. S.G. Shubin from CSS LPI under scientific supervision of V.K. Abalakin took part in ephemeris development for lunar retroreflectors. The program was based on the determination of the Moon's center coordinates using the dynamical model for the motion of the Sun, the planets, and the barycenter of Earth-Moon system relative to the barycenter of the Solar system; and for the motion of the Moon relative to the Earth center of mass in the orthogonal coordinate system prescribed by the Earth equator and standard epoch J2000.0. Ephemeris VSOP82 [9] and BDL82 [10] with Chebyschev polynomial expansion of the coordinates and velocities of the objects at the reference time moments with account for precession and nutation according to the most up-to-date expansions, libration of the Moon and finite speed of light were used.

In 1983 LLR experiments in Nauchny were discontinued because of the cancellation of Soviet lunar programs [8].

In 1984 CSS LPI started attempts to perform LLR observations with a 1 m telescope TPL-1 of a specially built for that purpose laser ranging station in Katzively (first one in Soviet network dedicated for LLR [11]) but no positive results were achieved.

In spring 1991 V.V. Shargorodsky and Yu.L. Kokurin suggested resuming observations of the lunar retroreflectors at the astronomical complex on the mount Maidanak. In fall 1991 V.N. Triapitsyn updated the software for computing the ephemerides of the lunar retroreflectors and adopted it for observations at the Maidanak complex. But because of drastic deterioration in the political and economic situation, observations of the Moon from Maidanak never started.

Below we present the list of groups which were involved in the investigation of potentials of the Lunar Laser Ranging, creation of equipment, measurements, computing ephemerides and data reduction.

<u>LPI:</u>

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Alyab'ev Viktor Aleksandrovich
Ovsyankin Mikhail Arsentievich
Nigmatullin Finis Khamitovich
Kuz'menko Nikolai Evgenievich
Topol'nikov Vitaly Aleksandrovich
Los' Evgeny Vasilievich
Ignatenko Yuri Vasilievich
Popov Vadim Gavrilovich
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Komarov Mikhail Vasilievich
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Shubin Sergei Grigorievich

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Lunichkin Georgy Anatolievich

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Kleimenov Eduard Sergeevich

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CrAO:

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Gershberg Roald Evgen'evich – chief astronomer of the Shajn Mirror Telescope

Mozhzherin Veniamin Mikhailovich - astronomer

Chernych Nikolai Stepanovich – astronomer

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