

# Processing and analysis of lunar laser ranging observations in Crimea in 1974–1984

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## Abstract

Analysis of lunar laser ranging (LLR) observational data since 1969 to present time has demonstrated that the LLR is an effective method of Solar System research. It has been proven by building the high-precision ephemeris of the Solar System: DE (USA), EPM (Russia), INPOP (France), and parameters of lunar orbital and rotational motion, as well as others (geodynamical, relativistic), determined with high accuracy by different authors. LLR observation database presently contains more than 24000 normal points. In USSR, LLR measurements were performed in CrAO (Crimea) on the Shajn 2.6 m telescope with an automated laser ranging system developed by the Lebedev Physical Institute [5], and in the time span of 1969 to 1984 there were obtained 1400 measurements. The accuracy of the measurements, according to literature [2, 6] was initially 3.0 m, and then was gradually improved to 0.6 m by 1978. Those measurements are not part in LLR observations database. Some of these observational data (176 photons for 1982–1984 and 103 normal points for earlier years) was stored in a CrAO facility in Katsiveli. The main purpose of our work was to process the Crimean observations (previously unpublished) with modern ephemeris EPM2017 [12], and to determine their place in the history of LLR. The real accuracy of these observations was estimated. The results of the processing and analysis are presented. A particularly interesting finding is related to the three normal points of Lunokhod 1 ranges obtained in 1974, which allowed Odile Calame to determine the rover's position with a few kilometers accuracy. Unfortunately, that was not enough to confirm the location of the rover at the McDonald observatory. As we see now, those three ranges had sub-meter accuracy and if CrAO gathered more data, Lunokhod 1 could have been found in that time.

## Short history of LLR in CrAO

The Crimean Astrophysical Observatory was the only place in the USSR where lunar laser ranging was performed. The history of the observations is summarized in Table 1. The first ranges (to the lunar surface) were obtained in 1962 and had the accuracy of 150 km. For the last ranges (1984), the accuracy 25 cm has been reported, however the estimate of accuracy of the found data is 2-3 times worse. The LLR observations to the lunar retroreflectors (since 1970) were obtained with 260 cm Shajn Reflector (Shajn's Zenith Telescope, ZTSH, see Figure 1). Three groups were involved: one from FIAN (Moscow), who developed the laser (N. G. Basov, Yu. L. Kokurin, S. G. Shubin and others), one from CrAO, who operated the telescope (under A. B. Severniy), and one from the Institute of Theoretical Astronomy in Leningrad, who processed the observations [1], under V. K. Abalakin.

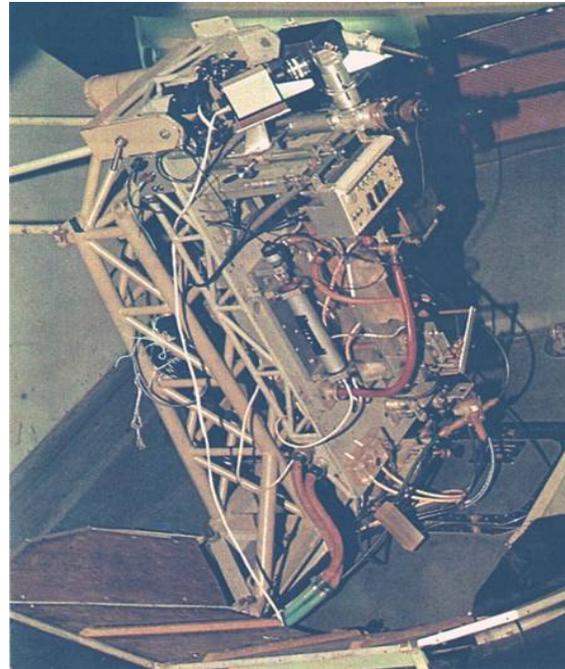
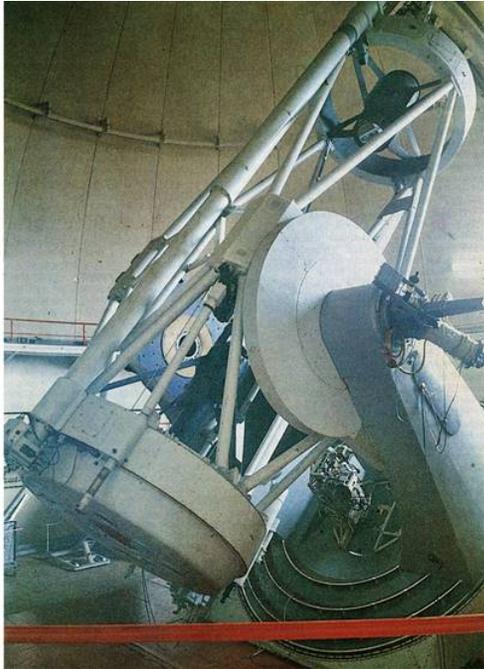


Figure 1: Shajn’s Zenith Telescope and laser installed at the Crimean Astrophysical Observatory

More than 1400 individual photon ranges have been obtained in 1970–1984. There was an international collaboration: both Soviet rovers have French retroreflector panels on them; also Soviet visitors went to the McDonald observatory (USA) and helped to locate Lunokhod 2. The measurement of the chord length “McDonald — Nauchny” was done with the accuracy of several meters [4]. The coordinates of the two observatories have been obtained with improved precision. Apparently the Soviet government prohibited to disclose the name of the town (Nauchny) where the observatory was, and the observations were published as made at Simeis. As a result, Calame called the chord “McDonald — Simeis”, while noticing that the determined location is different from Simeis.

Table 1. Evolution of CrAO LLR observations and their accuracy (1962–1984).

Year	Range accuracy	Hardware
1962	150 km (to the crater Albategnius)	Ruby laser (694.3 nm), 2-7 ms pulse, power 50–70 J
1965	200 m (to the crater Flammarion)	Laser with Q-switch modulation, 50 ns pulse, power 5–7 J
1970	3 m to Lunokhod 1	Upgraded hardware
1973–1978	0.9 m to Apollo 11/14/15, Lunokhod 1/2	Upgraded laser
1978–1982	0.6 m to Apollo 11/14/15, Lunokhod 2	Automatic control, regular ranges
1983–1984	0.25 m (not confirmed) to Apollo 15, Lunokhod 2	2–7 ns pulse

## LLR observations obtained in CrAO in 1973–1984

The observations were found on a shelf at Katsiveli, Crimea, in the form of old printouts done at an alphanumeric printer (Table 2). The data was not full: some ranges were provided without the values of electronic and geometric delays, some without meteorological data.

For records from 1982–1984 that did not have meteorological data in them, substitutions were used, either data from an archive of a meteorological station located near Nauchny, or records from other observations made at the same observatory in near time, or mean values from meteorological records for the day of observation. The CrAO LLR data has been re-digitized and is now available at the IAA RAS website [13]. It has the same format as was used by the McDonald observatory [7] at the time. The temperature, pressure, and relative humidity numbers are filled in all records.

Table 2. LLR observations at CrAO in 1973-1984.

Years	Meteorological data	Electronic and geometric delays	Number of ranges
1973–1981	-	-	103 normal points
1982	+/-	+	118 photons
1983	+/-	+	46 photons
1984	+/-	+	12 photons

## Processing of CrAO observations using the modern ephemeris

The 176 CrAO ranges (1982–1984) have been processed with ERA-8 software [9] using modern EPM ephemeris and retroreflector positions [10, 12].

The JPL KEOF EOP series [11] were used during the processing. It was earlier found [10] that they are better suited to old LLR observations than IERS C04 series. An attempt to determine the EOP (UT0 and VOL) from the CrAO observations themselves was unsuccessful due to low number of observations and insufficient accuracy.

The shooting time labels were provided in the UTC(SU) timescale. No tie between UTC(SU) and the international UTC was found for that time, but a bulletin for 1982 [3] lists UTC–UTC(SU) values between 23 and 27 microseconds. This corresponds to less than 1 cm change in one-way range. Since the observational data is much less accurate, the timescale was just treated as UTC.

Coordinates of the reference point of the telescope were determined from the LLR observations being processed. The results are:  $\lambda = 34^{\circ}.015782$  ( $1\sigma = 0^{\circ}.000001$ ),  $\rho \cos\phi = 4539377.06$  m ( $1\sigma = 8.5$  cm),  $\rho \sin\phi = 4466363.41$  m ( $1\sigma = 20$  cm). ( $\lambda$  and  $\phi$  are the longitude and latitude, respectively, while  $\rho$  is the third spherical coordinate.) This makes  $\rho = 6368229.4$  m,  $\phi =$

44°.535487. The determined coordinates are close (to several meters) to the ones determined in [4] in longitude and latitude, but differ by 30 m in radius: the value from [4] is 6368260 m.

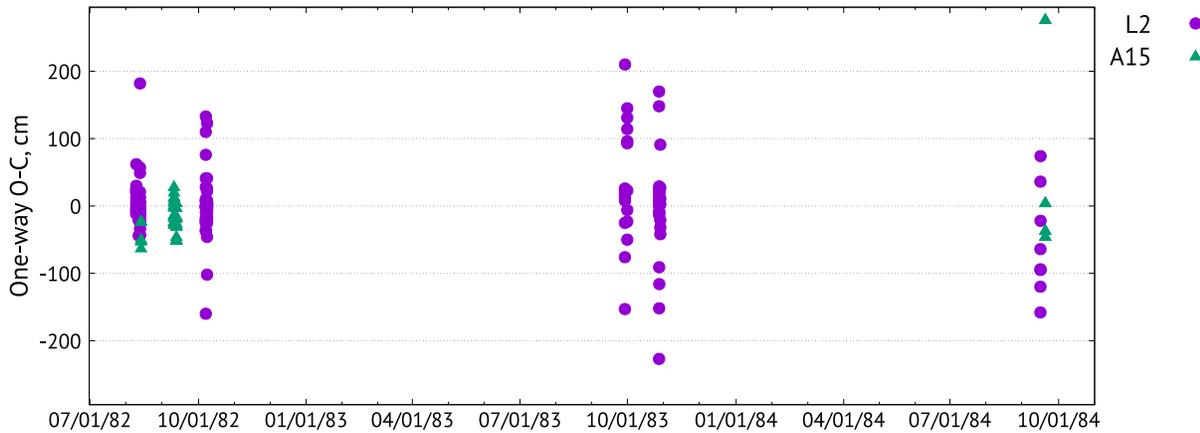


Figure 2: Residual values of the CrAO LLR observations

The residuals are shown at Figure 2. The root-mean-square (RMS) value of the residuals is 59 cm. If we filter out nine observations whose absolute value exceeds 1.5 m, 167 observations will be left, with the RMS of 41 cm.

### Three Lunokhod 1 ranges in 1974

Among the CrAO 1974–1981 data, three Lunokhod 1 ranges are present. The found printouts were in different format than the later 176 observations; they did not contain calibration data, nor meteorological data. They have been processed, nevertheless, and the found residuals were sub-meter (see Table 3).

Table 3. Three Lunokhod 1 normal points obtained from CrAO observations

Date and time of shooting	Delay (s)	Residual (one-way m)
28.05.1974 18:37:46.929988	2.4565319936	0.93
28.05.1974 19:51:32.251415	2.4648665413	-0.95
15.07.1974 01:42:05.114108	2.4755519847	-0.50

According to [4], there were “36 individual photons, on two nights, at an interval of 47 days”, so the data in Table 3 are probably normal points formed from these photons.

These ranges were available to Odile Calame (CERGA, France), who analyzed LLR observations from McDonald and CrAO simultaneously [4]. Lunokhod 1/2 ranges were available only from CrAO, while Apollo 14 ranges were available only from McDonald. Only Apollo 11 and Apollo 15 ranges were common to both observatories. Calame made an attempt to determine the location of Lunokhod 1: radius 1737.136 km, longitude  $-35^{\circ}.1537$ , latitude  $+38^{\circ}.3689$ .

Calame estimated the accuracy of this result as “few hundred kilometers”, but in fact this location is 3.7 kilometers off from what is presently determined by modern LLR measurements. The McDonald observatory tried to use Calame’s coordinates but never obtained ranges from Lunokhod 1.

It remains unclear why the Soviet team did not continue the Lunokhod 1 ranging after 1974. That, plus the unsuccessful attempt at the McDonald observatory, ultimately lead researchers to the conclusion that Lunokhod 1 is lost. The ranging of Lunokhod 1 resumed in 2010 at the Apache Point observatory, when the rover was spotted on the Lunar Reconnaissance Orbiter (LRO) images [8].

## Conclusion

The CrAO LLR observations, a joint effort by FIAN, CrAO, and ITA, were real and are confirmed by the present analysis. They were less precise than the LLR observations made by McDonald and CERGA observatories at the same time (RMS 20 and 17 cm, respectively [10]), and can bring no improvement to the present lunar ephemeris. However, there is probably more historical LLR data at CrAO, or copies at Grasse or McDonald observatories. There is an ongoing work to collect the remaining ranges and normal points.

The location of Lunokhod 1 probably could have been determined in mid-1970s if CrAO obtained more ranges, and if the international collaboration was more intensive. The re-discovery of the rover’s position from LRO data was made independently of CrAO and Calame’s work.

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