LUNAR LASER RANGING
stations and reflectors

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Lunar laser telemetry consists in determining the round-trip travel time of the light between a transmitter on the Earth and a reflector on the Moon, which is an equivalent measurement of the distance between these two points. Neil Armstrong put down the first reflector array in the Sea of Tranquillity in July 1969 and a few weeks later McDonald Observatory succeeded in detecting photons returned from a laser pulse sent to the Moon.

Afterwards, more reflector arrays have been placed by two American Apollo missions in 1971 (Apollo 14 and Apollo 15), and two Soviet automatic missions, Luna 17 (1970) and Luna 21 (1973) which carried French-built reflectors, Lunakhod 1 and 2. Except Lunakhod 1 from which the signal has been lost, the 4 other reflectors are still operating normally (Fig. 1).

The Apollo arrays consist of 3.8-cm diameter corner cubes mounted on an aluminium panel (100 for Apollo 11 and 14 and 300 for Apollo 15). The Lunakhod arrays have 14 triangularly faced corner cubes of 11-cm edge. The design of reflector arrays is straightforward: each corner cube reflects incident light back to its point of origin (Fig. 2).

Since 1970 there were few LLR observing stations. The first one was McDonald Observatory (2.7-m telescope) near Fort Davis, Texas (USA). It was fully dedicated to lunar ranging and ceased operation in 1985 after maintaining routine activities for more than 15 years. The transition was made in the mid-1980s to the McDonald Laser Ranging Station (0.76-m telescope) on two sites (Saddle and Mt. Fowlkes): MLRS1 (1983-1988) and MLRS2 (since 1988) which share lunar and artificial satellite ranging facilities (Fig. 3).

In the 1980s, two other stations have carried out Lunar Laser Ranging. The Haleakala Observatory on Maui, Hawaii (USA) produced high quality data over a few years around 1990. Since 1982, the CERGA station (Centre d'Etudes et de Recherche en Géodynamique et Astronomie) has been operating at the 'Observatoire de Côte d'Azur' (OCA) on the 'Plateau de Calern' near Grasse (France), with a 1.54-m Cassegrain telescope which replaced its Rubis laser by a YAG in 1987 (Fig. 4).

Occasionally some other artificial-satellite stations have performed successfully LLR observations such as in Australia and in Germany, but all the data used for the analyses come from the 3 observatories: McDonald, Haleakala and CERGA. Today, just two observatories are still operating: McDonald (MLRS2) and CERGA.

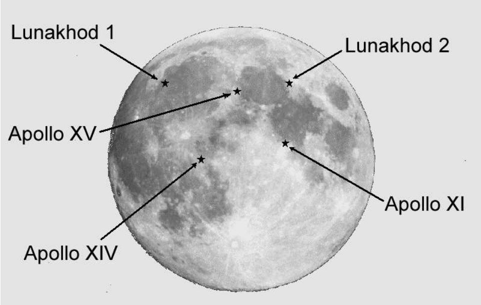

Fig. 1. Distribution of the reflectors on the lunar surface

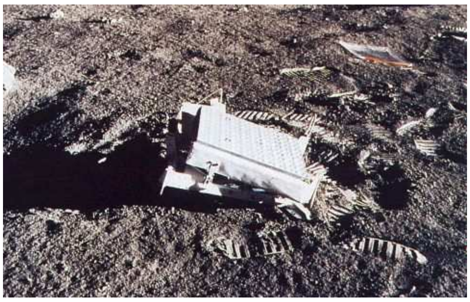

Fig. 2. Photography of the reflector array placed by Apollo 14

The principle of Lunar Laser Ranging is to fire laser pulses towards the target reflectors on the Moon, to receive back localised and recognizable signals and to measure the duration of the round-trip travel of the light. If the concept is elementary, it is in fact a real technical challenge.

At first, the performances of the observations depend on the quality of the time measurements. On average the duration of the round-trip flight is 2.5 seconds varying according to the lunar distance, the mean distance Earth-Moon being 385000 km. If one aims at a precision of 1 cm for the separation between transmitter and reflector, one needs an accuracy of the order of 0.1 nanosecond (10^{-10} second) in the measurement of the round-trip travel duration. The measure of the time is based on a very stable high frequency signal generated by a caesium atomic clock whose the frequency accuracy is better than 10^{-12} yielding an uncertainty below 10 picoseconds (10^{-11} second) over the journey of the light.

But several factors affect the precision of the measurements. The atmosphere induces a time delay which is difficult to estimate rigorously, probably between 50 and 100 picoseconds; it depends on temperature, pressure and humidity. The libration of the Moon makes an oscillation of the orientation of the array which produces, in worse cases, an unbiased scatter in distance of few centimeters (about 200 picoseconds in the time of flight). There are other sources of uncertainties such as the photodiodes connected to the start timer or the return detector.

At the French station operated by CERGA, a team has tested several approaches and has converged towards widths of about 200 picoseconds. And to improve the chance to trapping the right return photon several kinds of filtering are performed to eliminate the noisy photons as much as possible.
- The field stop of the photodiode prevents photons more than 10″ off the expected arrival direction from entering the detection channel.
- An interferential filter lets only the light at the laser wavelength (±0.12 nm) go through the detection system.
- The gate is open only during a small interval around the expected arrival time, typically ± 50 ns.

In these conditions, the precision of a measurement of the round-trip travel time of 'one photon' is of the order of 3 cm. With the most unfavourable librations this value can grow up to about 5 cm.

Nevertheless, the main problem stands elsewhere. The outgoing beam has a divergence of 3" to 4" after crossing the Earth atmosphere so that the size of the light spot on the Moon is about 7 km in diameter, which means that only one photon out of 10^9 impacts a reflector array. Besides the reflected beam has a significant angular divergence (12") due to the diffraction by the pupil of the reflector yielding a spot nearly 25 km back on the Earth. With a 1-meter telescope, only a fraction 10^{-9} of the photons is intercepted.

Finally, allowing for other factors, just one photon is detected out of 10^{20} emitted in the initial pulse. With the YAG laser of the CERGA (since 1987), the energy of the beam is about 300 mJ per pulse at a wavelength of 532 nanometers; it is equivalent to 10^{18} photons. That gives an average of one return every 100 pulses, or every 10 seconds, the laser system producing pulses with a typical rate of 10 pulses per second.

With ranges of few centimeters accuracy, the Lunar Laser is an extraordinary tool for gravitational physics, geodesy and geophysics. Over the years the major contributions are found in the improvement of the orbital and rotational motion of the Moon, the accurate assessment of the tidal dissipation, the determination of the gravitational moments, the observation of its free libration, the check of the equivalence principle for massive bodies, the realization and comparisons of reference systems and the monitoring of the Earth rotation.

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Fig. 3. McDonald Laser ranging station (Fort Davis, Texas)

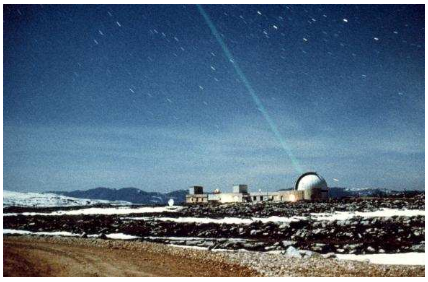

Fig. 4. CERGA Laser ranging station (Plateau de Calern, Caussols, France)

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