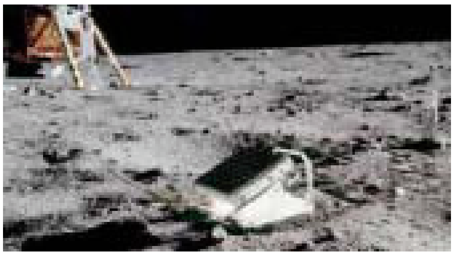
Lunar Laser Range Finding
The Legacy of Apollo and the Observatorie de la Côte D'Azur

By Barry Davidoff

Thirty five years after Neil Armstrong landed on the moon, man still visits Tranquility Base regularly. On many nights lasers fired from the Observatoire de la Côte D'Azur (OCA) and the McDonald Observatory in Texas bounce back from the reflectors left by the lunar explorers. The precisely timed impulses measure the distance between the earth and the moon with incredible precision.



The first laser reflector at Tranquility Base

Scientific experiments were a primary function of the Apollo program. On the first lunar landing there was limited time on the surface and weight in the Lunar Module so the Early Apollo Surface Experiments Package (EASEP) was developed consisting of a seismometer and a laser reflector. The prime contractor for both experiments was Bendix Corporation.

By measuring the exact time that a laser pulse takes to reach the moon and reflect back, the exact distance to the moon can be determined. In over 35 years of operation, the laser reflector has provided valuable information on the composition of the moon, plate tectonics and Einstein's theory of relativity.

The Apollo 11 laser reflector consists of 100 fused silica corner cubes, mounted in a 46 centimeters (18 inches) square aluminum panel. Each corner cube is designed to reflect the laser beam at exactly the same angle towards the point of origin.

A corner cube is only 3.8 centimeters (1.5 inches) in diameter and the laser reflector does not require any power. It will function on the moon's surface for at least thousands of years.

Close up of the corner cubes in the laser reflector

A second similar reflector was placed at Fra Mauro by the crew of Apollo 14 in January 1971. A larger reflector consisting of 300 corner cubes was part of the experiments of Apollo 15. The Soviet Union, not to be out distanced during the space race, placed on the two Soviet Lunakhods, smaller reflectors composed of 14 corner cubes. The reflectors were manufactured by Aerospatiale in Cannes, which is near OCA.

The distance from the earth to the moon was first estimated in the third century BC by Aristarchus of Samos using the time that it took for the moon to pass through the earth's shadow during a lunar eclipse. Ptolemy in the second century AD refined the measurements to 376,000 kms. for the distance (actual distance is 385,000 kms.) and 3,700 kms. for the lunar diameter. In the twentieth century radar pulses further defined the distance.

The assistance of Dr. Jean-Francois Mangin of OCA in providing information and photos is appreciated

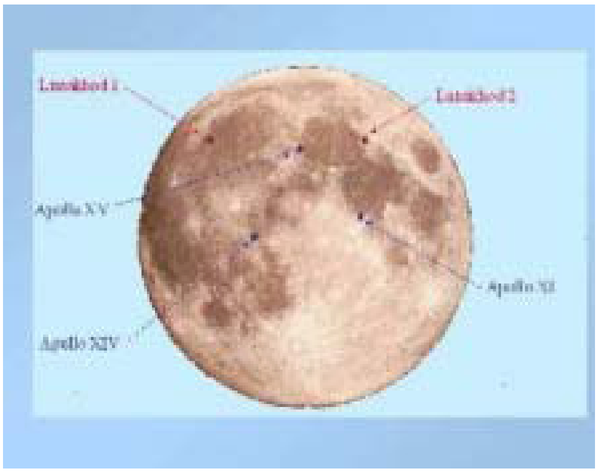
Replica of Lunakhod-Photo by Andi Wuestner

At the time the laser reflectors were placed on the moon, the distance to the moon was able to be determined by lasers with an accuracy of fifteen centimeters (6 inches). Improvements in technology, and especially the timing of the laser pulses, increased the accuracy by nearly a factor of 100. During a lunar eclipse on April 13, 2000 when there was particularly low interference, Dr. Jean-Francois Mangin and his team at OCA measured the lunar distance with an astonishing accuracy of 1.3 millimeters.

OCA and the McDonald Observatory near Ft. Davis, Texas are the two leading centers for lunar laser range finding experiments. A third observatory atop the Haleakala volcano in Hawaii was used during the Apollo program. When the lasers are fired at OCA during lunar ranging experiments at night, the craggy mountainside near Caussols, France is ablaze with spectacular colors as shown in the photos on the front cover and in bildgalleriet.

At OCA a laser is fired through the 1.54 meter (60.6 inch) Cassegrain telescope that has been exactly aimed at the laser reflector on the moon. The YAG (Yttrium, Aluminum, Garnet) laser beam passes through a mirror rotating at 10 times per second to split it into precise pulses. A cesium atomic clock at the observatory times each departing pulses. A cesium atomic clock at the observatory times each departing laser pulse with an accuracy of 10 picoseconds (10^{-12} seconds)

During the approximately 1½ seconds it takes for the laser to reach the moon, the beam spreads out to a width of about two kilometers. When the laser impulse strikes the reflector on the moon's surface, the incident beam is reflected back by the silica corner cubes at precisely the same angle towards OCA. The accuracy required to strike one of the laser reflectors on the moon is similar to using a rifle to hit a moving 10 kroner coin at a distance of 3.2 kilometers (2 miles).



Map of the five lunar laser reflectors

Since the YAG laser beam is a precise wavelength, the returning signal can be detected by a series of photodiodes at OCA. The photodiodes also are linked to the atomic clock at the observatory and the returning signal can be timed with an accuracy of 7 picoseconds. The exact time interval between the departing laser beam and the arrival of the return signal provides an extremely accurate measurement of the true distance to the moon since the speed of light is constant and well defined.

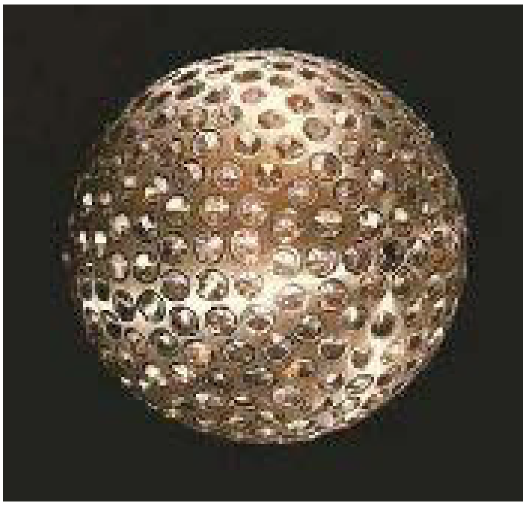
The Satellite Laser Ranging program at OCA uses the same equipment and bounces laser impulses off a series of orbiting satellites. The location of each satellite can be measured with an accuracy of less than one millimeter. The satellite ranging program has enabled the most accurate maps of the earth to be produced, which include fluctuations in local gravitational fields. It also has enabled differences in sea level to be plotted as part of climatic change. Satellite ranging is used to calibrate radar altimeters and Global Positioning Systems (GPS).

Thirty five years of lunar laser ranging has yielded important scientific results. The precise measurement showed that the moon's surface bulges outwards by as much as 10 centimeters (4 inches) during the lunar month due to the gravitational attraction of the sun and the earth. This compares with the greater movement of the earth, which is over half a meter, since the earth has a liquid core and most of its surface is covered by water. Scientists have concluded on the basis of the precise measurements that the moon has a partially melted liquid zone above its core. The existence of the liquid layer also is corroborated by data from the seismometers left during the Apollo program. Seismic data showed that the shock waves of moon quakes lost energy as they approached the lunar core.

Since lunar laser ranging provides measurements of great distances with the accuracy of millimeters there have been many important discoveries about plate tectonics on earth. The observatory in Hawaii is slowly moving to the Northwest at the rate of 70 millimeters a year. In the mere 35 years since the reflectors were placed on the moon, this tropical paradise has moved nearly 2½ meters closer towards to Siberia, while the Riviera, where OCA is located, is moving in a Northeasterly direction towards Switzerland at a slower rate. These changes in locations closely match the geophysical models. The lunar laser ranging results also have been verified by satellite laser ranging measurements taken from many more locations with even greater precision.

Lunar laser ranging has shown that the moon is receding from the earth at the rate of 3.7 centimeters (1.5 inches) a year. Simultaneously, the length of the earth day is increasing by one thousandth of a second every year. Both are due to the tidal effects of the oceans slowing the earth's rotation.

Precision measurements of the moon's orbit has provided the exact location and timing of solar and lunar eclipses back as far as 1400 BC.



LAGEOS I satellite covered by 426 corner cubes

The lunar and satellite laser ranging programs at OCA have provided confirmation of Einstein's Theory of Relativity. Exact measurements over 35 years has shown that the product of the gravitational constant and the earth's mass (GM) has remained unchanged.

Laser ranging also has provided important evidence that the mass and rotation of the earth cause distortions in space time, which is called Lense-Thirring drag. The LAGEOS I satellite, launched in 1976, and the LAGEOS II satellite, launched in 1992 are covered with reflecting corner cubes. After 100 million measurements by lasers of the two satellites' orbits it has been calculated that there is a distortion of about 2 meters per year as predicted by Einstein's Theory of Relativity. Further proof is being provided by the Gravity B Probe launched in April 2004.

OCA's lasers fired from the Plane de Calern