# Laser Ranging: Measuring the Moon's Distance

Among the scientific instruments placed on the moon by Neil Armstrong and Buz Aldrin in July 1969 was an array of 100 fused silica retroreflectors designed to return light pulses from earthbound lasers in a ranging experiment which is the only part of the Apollo 11 scientific package still operational. Light signals from short-pulse lasers aimed toward the lunar reflector have been regularly received by telescopes during the past year. The reflected signals are so faint that detectors attached to the telescopes are triggered by a single photoelectron, but are precise enough that the distance to the moon can be dependably measured to within 30 centimeters at present calibration levels. Analysis of the patterns found in the data received is markedly improving knowledge of the moon's orbit and of the telescope and reflector locations. Later, scientists plan to use this information to analyze some of the earth's peculiar motions, to measure continental drift, and to test gravitational theories.

The scientific team that developed the lunar reflector is headed by physicist Carroll Alley of the University of Maryland, who likes to point out that the experiment is cumulative in its results. Thus he feels that use of the French-built reflector recently landed on the Sea of Rains by the Soviet spacecraft Luna 17 will enhance the value of the data obtained from the current reflector located in the Sea of Tranquillity. Apollo 14, which is to be launched late next month, carries yet another reflector; if it is successfully placed in the Fra Muro region, the positions of the three reflectors will form a large triangle on the surface of the moon, thereby providing a good spread for measurement of the moon's rotations by differential ranging.

The first signals from the Apollo 11 reflector were received by the 305-cm telescope of the Lick Observatory in California during August 1969. Since that time the Lunar Ranging Experiment (LURE) team has made several hundred range determinations with the 272-cm telescope at the McDonald Observatory in Texas. The Air Force Cambridge Research Laboratory has an independent lunar ranging group, headed by Donald Eckhart, which has received signals from the reflector with a 152-cm metal mirror telescope in Arizona. A French ground station in the Pyrenees has obtained echoes from the American reflector, and a Russian team has attempted observations. A Japanese station also is expected to begin operation in the near future. The number of observing stations is important because many of the hoped-for results depend on the comparison of observations from several locations.

### Laser Ranging Components

The basic element in both the French and American lunar packages is the "corner reflector," which is a truncated glass cube with the property that incoming light from a wide range of directions is returned parallel to the incident beam. A light pulse from the earth spreads because of variations in the atmospheric index of refraction to form an image several kilometers across when it hits the moon. The curvature and irregularity of the lunar surface result in part of the pulse being reflected before the rest, as well as a poor return in the total amount of reflected light. Corner reflectors, however, increase the intensity of the returning beam compared to that reflected by the lunar surface; because of their small size, they return a sharp pulse suitable for precise timing.

Both coated and uncoated reflectors are used, with the silvered back surfaces of the coated type allowing much higher total reflection at the center of the returning light pattern. The French package landed by the Soviets contained 14 coated reflectors, whereas the American experiment has 100 of the uncoated variety, the larger number compensating to some extent for the lower reflective efficiency. The disadvantage of coated reflectors is that their silvered surface heats under the sun's rays, producing thermal gradients which cause distortion, so that the reflector can only be used during lunar night. Since many of the scientifically meaningful results are extracted from the range data by Fourier analysis, the American team thought that the missing signals would seriously bias some frequency components of the data and hence chose the less efficient but continuously usable uncoated reflector design.

The ground stations for the laser ranging experiment consist of a telescope, a source of laser light which is guided to the reflector target by passing it through the telescope in the reverse direction (Fig. 1), and timing equipment. The laser currently used by the LURE team is a Q-switched four-stage ruby crystal laser which transmits about 4 joules or $10^{19}$ photons, firing a 4-nanosecond pulse every 3 seconds when in operation. The telescope receives a reflected pulse of about 10 or 20 photons, but internal reflections and other losses within the instrument reduce the light by a factor of 10 so that the photomultiplier tube, which operates with about 7 percent efficiency, produces typically one photoelectron every ten shots. Filters with a bandwidth of 0.7 Å cut off light that is not at the laser frequency of 6943 Å, and a range gate opens for a preselected interval keyed to the expected arrival time so that the detector is active only for a few microseconds.

The arrival time of the returning signal or, equivalently, the range to the moon must therefore be known to an accuracy of less than a kilometer; otherwise the signal will be missed. The LURE range predictions are based on a new ephemeris, computed by J. D. Mulholland of the Jet Propulsion Laboratory in California, which appears to be an order of magnitude more accurate than that given in previous tables of the moon's position. The current almanac ephemeris—even with the best available corrections—has errors as large as 2 km, apparently arising in part from the neglect of planetary perturbations in analytic theories of the moon's motion. Mulholland's ephemeris is computed by direct numerical integration of the equations of motion; in his computer program he uses empirical representations for the effects of poorly understood processes, such as tidal dissipation, and chooses initial conditions for the integration from an analytic theory. The resulting predictions seem to have a mean range error of only a few hundred meters.

Roundtrip travel time to the moon for the light pulse is about 2.5 seconds.

This period is divided into a series of 50-nanosecond intervals by a frequency source at the McDonald Observatory. Results from 50 consecutive laser shots are accumulated in these intervals to distinguish actual returns from background light. An analog system provides a vernier scale for timing the outgoing pulse and the arriving single-photoelectron signal within the 50-nanosecond intervals. The precision of the timing circuits seems to be good enough for the experimenters to feel that they can get down to 0.1-nanosecond timing when a shorter pulse length laser is available.

Corrections are made for atmospheric delays, although essentially all that appears to be needed is an accurate measurement of the atmospheric pressure at the telescope site. Earlier it had been thought that the corrections might be more complicated. However, the LURE team now believes that it can make corrections for atmospheric delays to within less than 0.1 nanosecond.

Absolute accuracy obtained with the ranging system depends on the clocks used in the timing system. The LURE team uses four clocks that are continuously compared against each other. These are the crystal oscillator and an atomic clock on site in Texas, a tie-in to the low-frequency WWV signal of the National Bureau of Standards, and the Navy Loran C navigational timing signal.

### Putting Laser Ranging to Work

Perhaps the most important result of the laser ranging experiment so far has been to demonstrate that the system can operate at or near predicted levels of accuracy despite its complexity. With the current precision of calibration the LURE group is regularly measuring the time delay of the laser signal to within 2 nanoseconds. This translates to a one-way range uncertainty of 30 cm, when a standard value for the velocity of light is used; since astronomical and geophysical distances are normally measured with a length scale based on light travel time, uncertainties in the velocity of light do not enter in.

Although analysis of the lunar range data is just beginning, some results are already forthcoming. For example, a systematic pattern has been noted in the data that, to the LURE team, suggests corrections of the order of 100 meters in the present numbers for the mean distances and the eccentricity of the moon's orbit. These adjustments in the orbital parameters would imply a correction to the mass of the earth-moon system. Preliminary checks of the position of the McDonald telescope have also been made with the data, and the results appear to agree with the coordinates found with satellite geodesy.

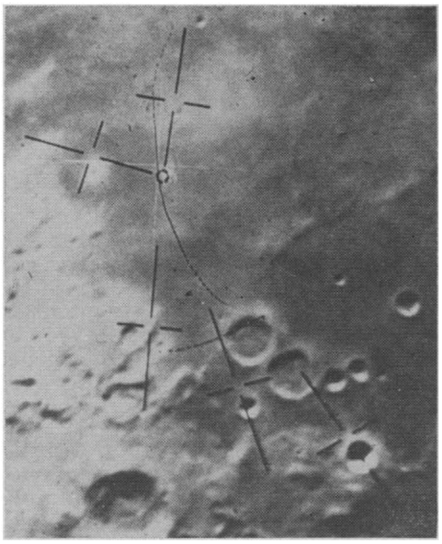

Fig. 1. View of the lunar target area with overlay for aiming the laser beam.

The scientific goals of the laser ranging program include a better understanding of three different kinds of phenomena, beginning with the motion of the earth and moon around each other. As the numerical integrations used in predicting the ephemeris are fitted to the observations, additional improvements in the knowledge of the motions of this system can be expected. Short range improvements are also expected by the LURE team in the accuracy with which telescope and reflector locations are known, leading to refined systems of geocentric and selenocentric coordinates and thereby eventually reducing a substantial source of error for all ground-based astronomy.

A second class of phenomena for which the LURE team expects more accurate information from laser ranging includes the motions of the earth and moon about their respective centers of mass. Study of the physical librations—the oscillations of the moon due to its shape and its gravitational attraction to the earth—will yield information on the moments of inertia of the moon and hence on the distribution of mass within it. On the earth the variation in the length of the day can potentially be measured much more accurately with the ranging technique than with the current photographic zenith tube method. More careful observations of the fluctuations in the rotation period may help scientists understand their cause, which is at present unknown, although interactions between the mantle and eddies in the core and wind-mountain interactions have both been proposed.

The motions of the mechanical pole of the earth are known to include a roughly circular movement with a yearly period and some oscillations or Chandler wobbles with a 14-month period. The Chandler wobbles appear to damp out and then are seemingly reexcited, possibly by earthquakes. The laser ranging data should allow greater accuracy, by a factor of 10, in observations of both of these polar motions.

Continental drift and gravitational theories are included in the third class of phenomena to which the LURE team hopes their observations will contribute significant new information. Although geological evidence from the Deep Sea Drilling program (*Science*, 30 October 1970, pp. 520–21) has established average past rates of drift for some of the main crustal plates, laser ranging can provide "real time" confirmation of this motion. It may be able to establish whether the sea-floor spreading is continuous or episodic, and hence give some evidence of the mechanism of action.

The classical experiments dealing with Einstein's general relativity theory provide little information about the higher order, nonlinear terms of the Riemann tensor, but over a period of years the laser ranging experiment may be able to give estimates of these coefficients. Lunar laser ranging, which was first proposed in Robert Dicke's Princeton University research laboratory, may also be able to distinguish between the Einstein theory and the Brans-Dicke gravitational theory if other tests, such as the recent data from Mariner 6 and 7 which seem to support Einstein's ideas, do not settle the question.

Future improvements in the laser ranging system such as the larger reflector array planned for Apollo 15 and the availability of very short pulse lasers of better beam quality should increase the amount of reflected light, making it possible for smaller telescopes to observe the signals, and should reduce the range uncertainty still further. The distance to the moon may soon be measured more accurately than are most distances here on earth.

—Allen L. Hammond