14. Laser Ranging Retroreflector

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CONCEPT OF THE EXPERIMENT

During the Apollo 15 mission, the third and largest U.S. laser ranging retroreflector (LRRR) was deployed on the lunar surface in the area near Hadley Rille. Ground-based stations can conduct short-pulse laser ranging during both lunar day and lunar night to this Apollo 15 array and the Apollo 11 (Sea of Tranquility area) and Apollo 14 (Fra Mauro area) retroreflector packages. These arrays are deployed at well-separated sites (fig. 1-1, sec. 1). The returned signal from the LRRR has an intensity 10 to 100 times greater than that reflected by the natural surface. The use of the LRRR eliminates the time-stretching of the pulse that results from the light being reflected back from different parts of the lunar surface. An observation program is being actively followed to obtain an extended sequence of high-precision Earth-Moon distance measurements that will, over a number of years, provide the data from which a variety of information about the Earth-Moon system can be derived (refs. 14-1 to 14-8). Preliminary analysis of ranging data from the three retroreflector arrays presently indicates that substantial corrections in their assumed position coordinates will be required. Full utilization of the Apollo arrays, as well as of the French-Russian array carried on Luna 17, will require an observing program lasting decades and using ground stations located around the world.

An obvious and immediate use of these data will be to define more precisely the motion of the Moon in its orbit. Another experimental result will be the measurement of the lunar librations—the irregular motions of the Moon about its center. The three Apollo arrays, which are well separated in longitude and latitude, will permit a completely geometrical separation of the lunar librations.

With two or three regularly observing stations well separated geographically, both components of polar motion as well as universal time can be determined. Periods as brief as 1 day in the rotation and polar motion of the Earth can be found if the data are frequent enough, but a considerably larger number of stations is needed if short-period variations are to be monitored regularly. The laser-ranging method, with its expected ± cm or better range accuracy, is capable of achieving an accuracy of a few centimeters for polar motion and crustal movements and of 100 μsec for universal time. Present accuracies, as determined by conventional astronomical observations, are 1 to 2 m for polar motion and approximately 5 msec for universal time (UT 1).

Accurate measurements of terrestial global plate motions by means of laser ranging may test whether the present rates are the same as the average past rates that have been deduced from observed displacements of geological features and remanent magnetic records.

Observations of the changes in the rotation rate of the Earth should provide clues into the nature of the core-mantle coupling and, hence, of the properties of the core and lower mantle. In addition, possible changes in the total angular momentum of the atmosphere of the Earth, which are believed to cause the annual and semiannual terms in the rotation rate

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of the Earth, may be sufficient to cause observable changes in the rotation rate of the Earth even for periods as short as a few days.

To begin checking present astronomical information concerning polar motion and Earth rotation, the major factor required is the improvement of the basic lunar ephemeris. The initial range uncertainties for the Apollo 11 and 14 retroreflectors were approximately 300 m. So far, using Apollo 11 LRRR data through July 1970, it has been possible to improve the range-prediction accuracy substantially. With the much greater frequency of data from the Apollo 11 LRRR that has been obtained since October 1970; data from the Apollo 14 LRRR that have been obtained since February 1971; and, now, data from the Apollo 15 LRRR, it should be possible to fit the lunar motion accurately as soon as the necessary analytical work has been done.

Finally, the sensitivity afforded by the presence of these reflecting arrays on the lunar surface will make it possible to use the Moon as a testing ground for gravitational theories. Many observers are interested in discovering whether the tensor theory of gravity is sufficient or if a scalar component is necessary as has been suggested. A definitive test of the hypotheses may be obtained by monitoring the motion of the Moon. Additionally, the possibility exists of seeing some very small but important effects in the motion of the Moon that are predicted by the general theory of relativity.

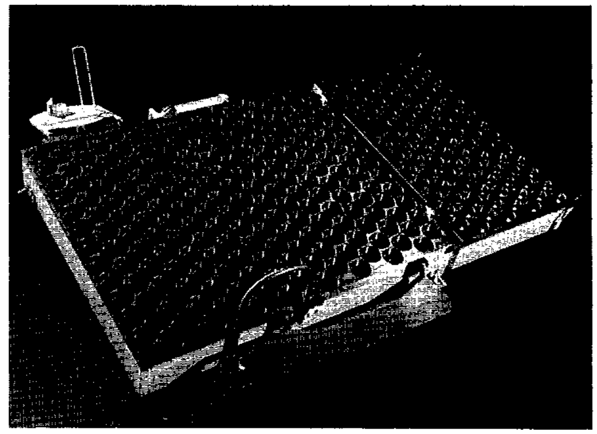

FIGURE 14-1.–Apollo 15 LRRR in deployed configuration.

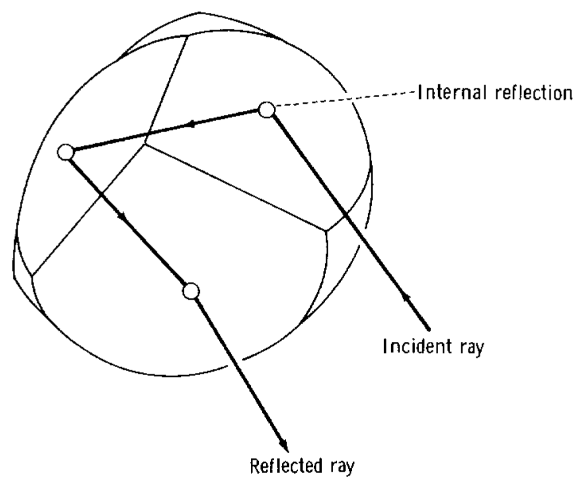

FIGURE 14-2.–Corner cube, showing how a light beam is reflected.

PROPERTIES OF THE LRRR ARRAYS

Each of the three arrays is a wholly passive device containing small, fused-silica corner cubes with front-face diameters of 3.8 cm. The Apollo 11 (ref. 14-9) and 14 (ref. 14-10) arrays are almost identical; each array contains 100 corner cubes. The Apollo 15 LRRR (fig. 14-1) contains 300 small, fused-silica corner cubes. Each corner cube in the array has the property of reflecting light parallel to the incident direction; that is, a light beam incident on a corner cube is internally reflected in sequence from the three back faces and then returned along a path parallel to the incident beam (fig. 14-2). This parallelism between the reflected and incident beams ensures that the reflected laser pulse will return to the vicinity of origin on the Earth.

The temperature gradients in the individual corner cubes are minimized by recessing each reflector by half its diameter in a circular socket. Each individual reflector is tab-mounted between two Teflon rings to afford the maximum thermal isolation (fig. 14-3). The mechanical mounting structure also is used to provide passive thermal control by means of its surface properties. A comparison of the calculated thermal performance expected from the Apollo 11, 14, and 15 arrays is shown in figure 14-4. During storage, transportation, handling, and flight, a transparent polyester cover assembly protects the arrays from dust and other contamination.

Mechanically, the Apollo 15 array consists of a hinged two-panel assembly (one panel containing 204 reflectors and the other containing 96 reflectors) mounted on a deployment-leg assembly. This leg was

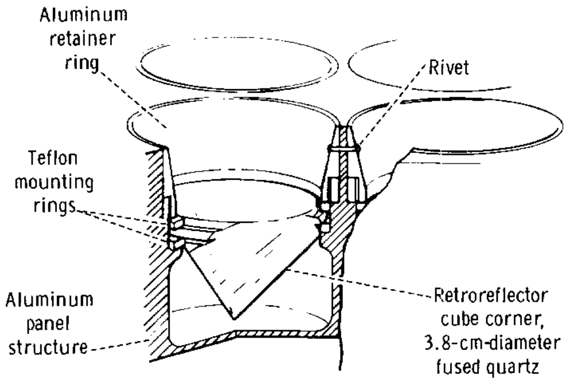

FIGURE 14-3.–Cutaway drawing of corner-cube mounting.

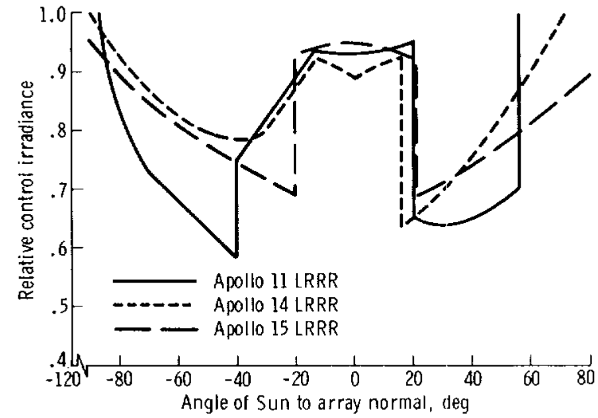

FIGURE 14-4.–Comparison of calculated thermal performance expected from Apollo 11, 14, and 15 LRRR arrays.

extended in deployment to support the retroreflector array at an elevation of approximately 26° to the lunar surface (fig. 14-5). In both panels, the cubes are arranged in a close-packed configuration to minimize the weight and overall size of the array. A comparison of these parameters for the three Apollo arrays is given in table 14-I. A Sun-compass assembly attached to the larger panel provides azimuthal alinement of the arrays with respect to the Sun, and a bubble level provides alinement with the lunar horizontal.

The Apollo 15 LRRR was deployed during the first period of extravehicular activity approximately 43 m southwest of the Apollo lunar surface experiments package central station (that is, approximately 140 m west of the lunar module). Leveling and alinement, to point the array toward the center of the Earth libration pattern, were accomplished with no

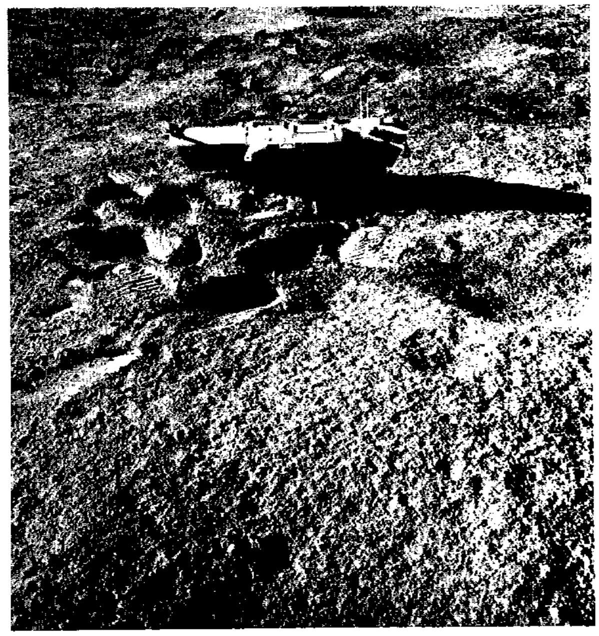

FIGURE 14-5.–Apollo 15 LRRR array deployed on lunar surface (AS15-85-11469).

difficulty. As a result of contingencies during the lunar-surface phase of the mission, photographic documentation was insufficient to determine deployment accuracy. However, both the astronauts' voice record and subsequent debriefing indicate that the array was properly deployed on the lunar surface.

Successful range measurements to the Apollo 15 array were first made from the McDonald Observatory of the University of Texas on August 3, 1971. In fact, a few returns had been received the preceding day, but these returns were not recognized until later

TABLE 14-I.–*Apollo LRRR Array Particulars*

Parameter	*Apollo 11*	*Apollo 14*	*Apollo 15*
Size, cm			
Height (stowed) . .	29.2	30.0	30.0
Width (stowed) . .	68.6	63.8	69.5
Width (deployed) .	68.6	63.8	105.2
Length	66.0	64.8	64.8
Weight, kg	23.59	20.41	36.20
Number of retro-reflectors	100	100	300
Retroreflector size, cm . . . . (front-face diameter)	3.8	3.8	3.8

because of heavy noise blanking that resulted from the initial range uncertainty. Experience thus far indicates that no serious degradation occurred during lunar module ascent-stage firing. Visual guiding of the telescope on the Apollo 15 site is facilitated by nearby lunar landmarks, which should aid other stations in their acquisition of this retroreflector array. A firing record for the Apollo 15 LRRR is given in table 14-II.

GROUND-STATION OPERATION

At present, range measurements to all three retroreflector packages at nearly all lunar phases are being made at the McDonald Observatory with NASA support. A line drawing of the laser-ranging station at the McDonald Observatory is shown in figure 14-6.

The present accuracy of ±30 cm for the lunar-distance measurements at the McDonald Observatory is limited mainly by problems in calibrating the electronic time delays in the system. The installation of a new calibration system is planned for late 1971; this system will, in effect, eliminate the time delays by using the same photomultiplier and electronics for both the transmitted pulse and the received pulse. Thus, an accuracy of ±15 cm is expected by the beginning of 1972.

The ruby-laser system presently being used at the McDonald Observatory gives 3-J pulses with a repetition rate of one every 3 sec. The total pulse length between the 10-percent-intensity points is 4 nsec. The root-mean-square variation in the observed transit time, caused by the laser-pulse length and the jitter in the photomultiplier receiving the returned signal, is 2

TABLE 14-II.—*Record of Firings for the Apollo 15 LRRR*

[McDonald Observatory, September 13, 1971]

Date, 1971	*Time, c.d.t*	*Number of laser firings*	*Number of returns*	*Comments*
Aug. 2	8:00 to 10:00 p.m.	490	4	Returns heavily noise-blanked by uncertainty in range
Aug. 3	8:30 to 10:30 p.m.	300	19	
Aug. 4	10:30 to 12:20 p.m.	400	32	
Aug. 5 to 6	11:00 p.m. to 1:00 a.m.	700	18	
Aug. 7	12:00 p.m. to 2:00 a.m.	150	24	
Aug. 8	2:00 to 4:00 a.m.	80	14	
Aug. 12	5:30 to 8:30 a.m.	150	21	
	10:10 to 10:30 a.m.	127	6	
Aug. 14	6:15 to 7:30 a.m.	50	0	Stopped by clouds
	8:00 to 8:45 a.m.	50	6	
Aug. 26	8:00 to 9:00 p.m.	100	0	Partly cloudy, computer-guided
Aug. 28	7:30 to 9:30 p.m.	200	12	
Aug. 29	7:30 to 9:30 p.m.	200	19	
Aug. 30	7:30 to 9:30 p.m.	150	13	
Aug. 31	10:00 to 11:00 p.m.	200	15	Extremely good return for the conditions;
	12:30 to 1:20 a.m.	50	7	i.e., 3 arc-sec seeing
Sept. 10	6:30 to 7:45 a.m.	100	25	Returns on 6 successive shots
Sept. 11	5:30 to 7:00 a.m.	100	30	Best signal so far for an extended run on any corner
Sept. 12	6:00 to 8:00 a.m.	180	13	Computer-guided
Sept. 13	6:25 to 7:00 a.m.	30	6	Computer-guided
Totals[a]		3807	284	[b]0.075 return/shot

[a]Comparative signals on the other two corner reflectors for the same period: Apollo 11 LRRR, 4130 shots, 150 returns, 0.037 return/shot; Apollo 14 LRRR, 5045 shots, 243 returns, 0.048 return/shot.

[b]The Apollo 15 returns will appear depressed because of the inability of the McDonald Observatory electronics to detect the multiple returns on days such as September 10. The smaller corner reflectors left by Apollo 11 and Apollo 14 will only rarely produce multiple-photoelectron returns. Thus, the improvement in signal brought about by the larger reflector is underestimated when calculated in this manner.

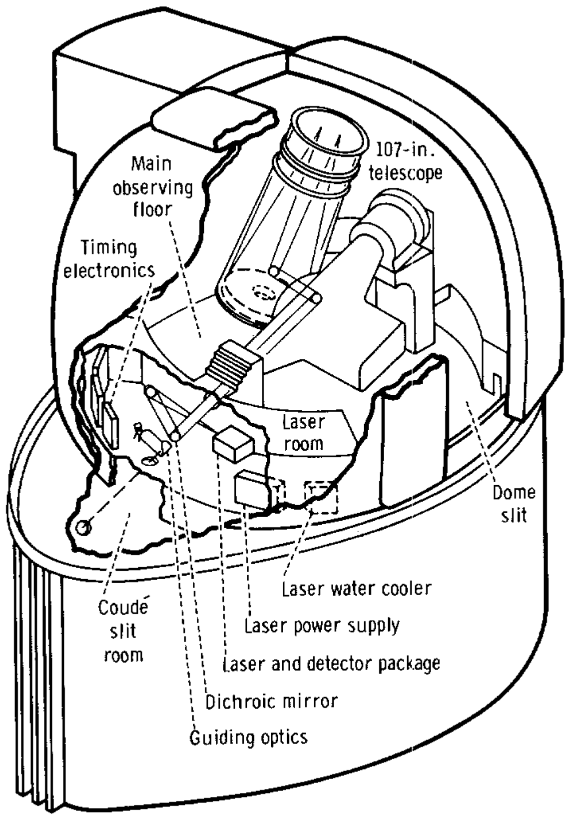

FIGURE 14-6.–Laser-ranging station at McDonald Observatory.

nsec. This variation results in the present ±30-cm statistical uncertainty for a single shot. Improvement to less than 1-nsec (±15-cm) statistical uncertainty is expected by averaging the range residuals over a period of a few minutes.

The uncertainty in the range correction for the effect of the atmosphere has been shown to be less than 6 cm up to zenith angles of 70° (ref. 14-2). This result was based on using the surface value of the atmospheric refractive index as a predictor for the correction, as is often done in radio work. Recently, it has been pointed out that very much better corrections for the optical case can be obtained by using the surface pressure as the predictor (refs. 14-11, 14-12, and 14-13). It now seems likely that the total error in the range correction for zenith angles of up to 70° will be less than 1 cm for normal atmospheric conditions.

Present indications are that lasers will be available shortly with reduced beam divergence, much shorter pulse lengths, and sufficient power to permit lunar ranging. The use of subnanosecond laser pulses will permit significantly greater measurement accuracy. The laser system proposed for the Lunar Ranging Experiment Team ranging station planned in Hawaii will have a 0.2-nsec pulse length, and it is expected that a short pulse length will be tried very soon at the McDonald Observatory. With care, an accuracy of 0.1 nsec seems achievable for the timing electronics. The accuracy of range data obtainable using a 0.2-nsec-pulse-length laser should be 3 cm or better, including an allowance of approximately 1 cm for the uncertainty in the atmospheric corrections at 70° from the zenith.

SUMMARY

With the Apollo 11 and 14 arrays, the placing of the Apollo 15 retroreflector array completes a three-array network. The larger signals obtainable with this array provide for a greater frequency of returns and will allow laser ranging to be carried out with telescopes of smaller aperture. This fact should encourage participation by a number of ground stations in other countries in monitoring the variations in the lunar distance by using these arrays, which give every indication of providing primary benchmarks on the lunar surface for years to come.

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