FINAL REPORT

LASER RANGING RETRO-REFLECTOR EXPERIMENT

Contract NAS 9-11025

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Abstract

In July 1969 the Apollo 11 astronauts placed an array of optical retro-reflectors on the surface of the moon. In February 1971, during the Apollo 14 mission, a second laser ranging retro-reflector was deployed on the lunar surface near Fra Mauro. During the Apollo 15 mission in July 1971, the third and largest U.S. laser ranging retro-reflector was deployed in the area near Hadley Rille. This report focuses on the Apollo 14 and 15 arrays, and discusses the experiments status.

History:

The lunar laser ranging experiment had its origins in the late 1950's in the gravitational research program at Princeton University. R. H. Dicke and his co-workers were considering ways to look for possible slow changes in the gravitational constant G by precision tracking of a very dense artificial satellite in a high-altitude orbit. The use of optical retroreflectors on the satellite and pulsed searchlight illumination from the ground to measure angular motion with respect to the stars was one of the methods considered in detail. When pulsed ruby lasers came along in 1960, and particularly Q-switched ones in 1961, it became clear that laser range measurements to retroreflectors on artificial satellites and on the moon would provide much more accurate tracking information. The first written text dealing with the problems of lunar laser ranging was prepared by J. E. Faller in 1962 and circulated to colleagues at Princeton and the National Bureau of Standards. He envisioned semi-soft landing of a retroreflector by one of the Ranger missions, and included a picture of a cube-corner reflector mounted in a self-righting silicone rubber package.

In 1962 L. D. Smullin and G. Fiocco at MIT succeeded in observing laser light pulses reflected from the lunar surface using a laser with millisecond pulse length. Additional measurements of this kind were reported by Graszuk *et al*. from the Crimean Astrophysical Observatory, and later Kokurin *et al*. reported successful results using a Q-switch ruby laser. Plans for the use of corner reflectors on an artificial satellite were described by H. H. Plotkin in 1963. Successful satellite range measurements were obtained soon after the Explorer XXII satellite was launched in 1964.

The scientific objectives achievable through high-accuracy range measurements to lunar retroreflectors, as perceived in 1964, included the following: 1) a much improved lunar orbit; 2) determination of the location of the retroreflectors with respect to the lunar center of mass; 3) study of the lunar physical librations (angular motions about the center of mass due to gravitational torques on the moon); 4) determinations of the locations of ground stations on the earth from which range observations were made; and 5) an accurate check on gravitational theory, through a search for deviations from the calculated range after all known parameters in the problem had been adjusted. An article describing the advantages of optical retroreflectors for lunar distance measurements was submitted for publication to the Journal of Geophysical Research in late 1964. Intensive efforts to develop a lunar ranging experiment were started at that time by a loosely organized group, which included most of the authors of the paper. A design study was carried out by the group, and a proposal for the experiment was submitted to NASA in December, 1965. A specific study of design questions related to the operation of retroreflectors on the lunar surface which was carried out by J. E. Faller at NBS, was included in the proposal.

The conclusions from Faller's study indicated that a reflector panel containing a number of solid fused silica corner reflectors roughly 4 cm in diameter would be capable of maintaining nearly diffraction limited performance under direct solar illumination and despite the severe temperature changes which take place on the lunar surface. Strong emphasis was placed on the importance of having the retroreflectors capable of operation even during the lunar day, in order to avoid the loss of data during the illuminated half of each month. A study of the diffraction pattern expected for a corner reflector with complex reflection coefficients was started at the University of Maryland. A successful test of the performance of solid fused silica corner reflectors under simulated lunar surface conditions with direct solar illumination was carried out at the Goddard Space Flight Center in 1966.

Basic Array Design

The basic array design results from the need to meet and simultaneously satisfy many different and sometimes conflicting requirements. In an ideal environment, the choice would be relatively simple since for a given geometry and allowable weight (payload), the return signal is maximized by using a single diffraction-limited retroreflector as large as weight restrictions and fabrication techniques will permit. This can be seen by noting that while the number of corners is proportional to $1/\ell^3$ (ℓ being a characteristic dimension of a corner), the collecting area (on the moon) is proportional to ℓ^2 times the number of corners and therefore varies as $1/\ell$. The returned spot area on earth will (as a result of diffraction) vary as $1/\ell^2$. The ranging efficiency is proportional to the retroreflecting area on the moon divided by the area on the earth over which the returning light is spread. This results in an overall efficiency which varies directly as ℓ. To take a specific example, the ratio of efficiencies for a fixed total mass m between a single large reflector and an array of 100 smaller reflectors is given by

$$\frac{m^{1/3}}{(m/100)^{1/3}} \approx 4.6 \quad .$$

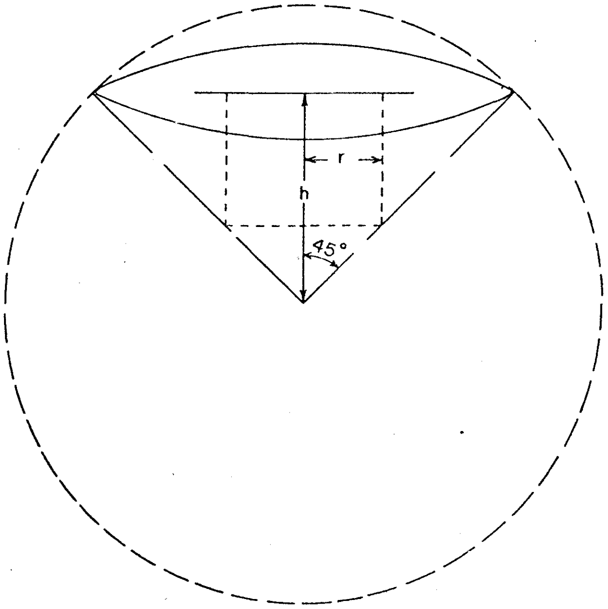
That is (other things being equal) a single large corner cube would result in a signal strength 4.6 times larger than 100 smaller cubes of the same total mass.

Two aspects of the practical problem which vitiate this conclusion are: (i) a displacement of the returned laser beam as a result of the relative velocity between the moon and the laser transmitter (velocity aberration) and (ii) the wide temperature viration on the moon as well as the exposure of the retroreflector to direct sunlight essentially half the time. The velocity aberration displaces the center of the returned diffraction pattern between 1.5 and 2 km and thereby limits the diameter of the diffraction-limited retroreflector that can be used to approximately 12 cm unless different and separated telescopes are used for transmitting and receiving. Further, due to the variability in the position of the returning signal over a month, either the transmitter or the receiver would need to be transportable between several sites in order for a separated system to provide much more than a factor of two in overall enhancement of the detectable signal.

For the case in which laser light is transmitted and received at the same location, the loss in efficiency that results from using a large number of smaller diameter corners is almost exactly compensated by the increased diffraction spreading of each corner which places the transmitter-receiver site higher up the side of the returned diffraction pattern. These two effects result in essentially the same optical efficiency for a given payload weight for corners ranging from approximately 3.8 to 12 cm in diameter. With the use of a corner smaller than 3.8 cm, an overall loss in efficiency is experienced because for that size corner the single transmitting and receiving site is already (for all practical purposes) at the center of the peak of the returned diffraction pattern and further diffraction spreading only serves then to reduce the intensity at the receiver aperture.

The choice of fused silica was a result of (i) the known radiation resistance of certain varieties of synthetic fused silica, (ii) its known stability over the range -65 °C to 100 °C (the primary 36" fused silica mirror of Stratoscope II was tested at -65 °C over long periods of time and found to keep its $\lambda/50$ figure well), (iii) its low expansion coefficient, (iv) its high resistance to thermal stresses, and (v) its high transparency to most of the wavelengths present in solar radiation.

To calculate the effects of the lunar thermal environment we require the size of temperature gradients induced in the cubes so that the retro-reflected wavefront distortion and thereby the resulting far field diffraction pattern can be calculated.



Simplified corner model.

To appreciate the magnitude of the thermal problem, consider the following calculation based on a particularly simple approximating geometry for an optical corner (See figure above). We first derive the resulting temperature distribution, and then, by using the temperature coefficient for the refractive index change of fused silica (the effects of expansion are negligible because of its low coefficient), calculate the resulting wavefront distortion which will give a measure of the deviation from diffraction limited performance. We take a cone with a half angle of 45° and height h as a thermal model of a corner reflector; we assume a uniform thermal input A/cm^3 throughout the volume, and treat the problem mathematically as that of a spherical sector (which includes a cap over the cone representing the corner). No heat flow across the (insulated) sides is allowed. The problem has azimuthal symmetry, and in the steady state condition, surface heating will just be balanced by the radiation from the front surface. For a sphere of thermal conductivity K with uniform volume heating, the equilibrium temperature distribution is given by

$$T = \alpha - \beta\rho^2$$

where $\beta = (A/6K)$ and ρ is the distance from the apex of the cone. With the above temperature distribution and for incident light parallel to the axis of the corner as represented by the cone, the variation in optical path with distance r from the axis is given by

$$\Delta S = -2 \frac{dn}{dT} \beta h r^2 \qquad ;$$

a typical integration path is shown dotted in the above figure. This path variation corresponds to the wavefront emerging from the retroreflector with a radius of curvature R given by

$$\frac{1}{R} = 4 \beta h \frac{dn}{dT} \qquad .$$

The angular radius θ_L of the resulting returned beam of light (ignoring diffraction) is then

$$\theta_L = \frac{h}{R} = 4\ \beta\ h^2 \frac{dn}{dT} \quad .$$

For diffraction alone, the angular radius at which the intensity falls to half maximum is $\theta_{1/2} = (0.52)(\lambda/2\ h)$. Accordingly, we have $\theta_L = \theta_{1/2}$ for a cone height h_c given by

$$h_c^3 = \frac{0.39\ \lambda\ K}{A(dn/dT)} \quad .$$

Substituting $dn/dT = 9 \times 10^{-6}$ for fused silica, $K = 0.0028$ cal $cm^{-1} sec^{-1}$ $°K^{-1}$, $\lambda = 0.7 \times 10^{-4}$ cm, and assuming that 1% of the incident light is absorbed per cm, $A = (0.01/15)$ cal $cm^{-3} sec^{-1}$ and the above gives

$$h_c^3 = (8.5 \times 10^{-3}/A) = 13\ cm^3 \quad \text{or} \quad h_c = 2.35\ cm \quad .$$

This corresponds to an initial diameter for the reflector of about 4.7 cm. For appreciably larger uncoated retroreflectors the thermal spreading of the returned beam increases quadratically with size. For the case of a 4.7 cm diameter "cube" ($h = 2.35$ cm), the maximum path difference $2(dn/dT)\ \beta\ h^3$ amounts to $\lambda/7$.

This and other similar calculations which were carried out in the initial analysis as well as the results of a detailed computer analysis for a variety of cases (performed by Arthur D. Little, Inc.) produced essentially this same conclusion: the realization of essentially diffraction limited performance during both the lunar night and day requires the use of small-sized corners (of this size or smaller).

Detailed optical analysis shows that polarization effects which result from using total internal reflection reduce as well as alter the intensity distribution in the central Airy disc. However, in order to increase the lifetime of the array and to avoid added thermal distortion, we accepted about a two-thirds reduction in signal strength by relying on total internal reflection rather than aluminizing the back surfaces of the individual retroreflectors which would have substantially eliminated this polarization effect on the far field energy distribution.

The basic observation, then, that dictated the choice of 3.8 cm as the diameter of the corners was the following: use of this smallest still-efficient size made it possible to minimize the thermal gradients that distort the individual cube-corner diffraction patterns and so achieve essentially diffraction-limited performance throughout the lunar day as well as during the lunar night.

In the initial analysis the possibility of using open corners was considered. However the question of fabricating diffraction limited open corners is a critical one. Solid corners are easier to make, had been made, and as such required no feasibility study. (The basic reason for the easier fabrication of solid cubes is that one is required to work only with external surfaces. An open cube, at least at first glance, involves work with internal surfaces or an "assembly" procedure either of which poses a number of difficulties.) As a result a pragmatic decision was made to fly arrays of solid retroreflector cubes.

The temperature gradients in the individual corner cubes are further 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; the mechanical mounting structure also provides passive thermal control by means of its surface properties.

During storage, transportation, handling, and flight a transparent polyester cover assembly protects the arrays from dust and other contamination. The Apollo crews remove this cover at the time of deployment.

Lunar Retro-reflector Packages:

The Apollo 11 reflector package which was placed on the moon on July 20, 1969 contained 100 solid fused silica corner reflectors mounted in a 46 cm square aluminum panel. The corners were 3.8 cm in diameter and recessed by 1.9 cm into circular holes in the panel for thermal control purposes. Provisions were made for tipping the reflector panel so that it pointed roughly toward the earth in order to maximize the effective cross-sectional area. The optical librations of the moon (i.e., apparent rotations of the moon due to the fact that we are observing it from somewhat different directions at different times) cause light transmitted from the earth to hit the reflectors at angles of up to about 11° to the normal. Even though the illuminated spot on the moon is typically 4 to 6 km in diameter, the fact that each corner reflector sends the light hitting it back in almost the same direction it came from causes the expected return signal at the earth from the reflector panel to be 10 to 100 times larger than the reflected intensity from the lunar surface. Successful range measurements to this array were first achieved from the Lick Observatory on August 1, 1969. Soon afterwards, returned signals were obtained with a high confidence level at McDonald also. Successful range measurements to the Apollo 11 reflector have also been reported by the Air Force Cambridge Research Laboratories Lunar Ranging Observatory which was in Arizona; the Pic du Midi Observatory in France; and the Tokyo Astronomical Observatory in Japan.

Four additional reflector panels have been placed at other locations on the lunar surface since 1969. The first was a French-built package of 14 glass corner reflectors, each 11 cm on an edge, carried to the moon by the Soviet spacecraft Luna 17 in November 1970. The package was mounted on the eight-wheeled lunar exploration vehicle Lunakhod 1. Return signals from it have been observed by a Soviet group using the 2.6 m (102") telescope at the Crimean Astrophysical Observatory and by a French group using the 1.06 m (42") telescope at the Pic du Midi Observatory. The package was not designed to give return signals during lunar day. Unfortunately, we know of no observed returns which have been reported since the first few months after landing. The reflector thus may have been coated with dust stirred up during surface explorations.

The next two lunar reflector arrays were carried on the Apollo 14 and 15 missions. The retroreflectors used in both arrays were similar to those employed for Apollo 11. The overall design of the Apollo 14 array is very similar to that for Apollo 11.

The Apollo 14 LRRR is a wholly passive device containing an array of 100 small, fused-silica corner cubes, each 3.8 cm in diameter. The Apollo 14 LRRR was deployed during the first period of extravehicular activity approximately 30 m west of the central station; thus, the array was placed approximately 200 m west of the lunar module (LM). Leveling and alinement to point the normal-to-the-array face toward the center of the Earth libration pattern was accomplished with no difficulty.

The Apollo 14 LRRR differs from the earlier Apollo 11 design in only two main aspects:

(1) The array cavity design was changed to increase the mechanical half-angle taper from 1.5° to 6° to decrease the obscuration and thereby increase the array optical efficiency approximately 20 to 30% for off-axis Earth positions.

(2) The supporting pallet is lighter and somewhat simpler in design. To be exact the Apollo 14 retroreflector weighed 20.41 kg as compared to the final weight of the Apollo 11 array which was 23.59 kg.

Successful range measurements to the Apollo 14 array were first made from the McDonald Observatory of the University of Texas on February 5, 1971, the day on which the LRRR was deployed by the crew. Ranging subsequent to LM liftoff indicated that no serious degradation of the retroreflectors has occurred as a result of the ascent-stage engine burn.

The Apollo 15 LRRR is larger containing 300 small, fused-silica corner cubes and weighed 36.20 kg. The larger strength obtainable with this array provides for a greater frequency of returns and, accordingly, will allow laser ranging to be carried out with telescopes of smaller aperture. This fact has encouraged participation and planned participation by a number of laser ranging stations in other countries.

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 extended in deployment to support the retroreflector array at an elevation of approximately 26° to the lunar surface. In both panels, the cubes are arranged in a close-packed configuration to minimize the weight and overall size of the array. 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 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 because of heavy noise blanking that resulted from the initial range uncertainty. 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. Returns from this array have been obtained by groups from France, the Soviet Union, the Smithsonian Astrophysical Observatory, and the Air Force Cambridge Research Laboratories.

A major purpose in making the Apollo 15 array larger was to permit regular observations with simpler ground equipment for groups which are mainly interested in obtaining geophysical information, and who therefore don't have to observe more than one reflector. This is important because a number of permanent stations located on the different continents are needed for determining polar motion and earth rotation regularly with high accuracy, as well as several movable lunar ranging stations for monitoring crustal movements at a large number of points on the earth's surface.

The fifth reflector package recently was carried to the moon by Luna 21, which landed on January 14, 1973. It is a French-built package similar to the one carried by Luna 17, and is mounted on Lunakhod 2. Return signals from it were obtained by the McDonald Observatory during the first and second lunar nights after landing. French scientists from the Ecole Polytechnique in Paris took part in the initial measurements, the results of which were reported in a joint Soviet-French-U.S. article. Unfortunately, no later returns from Lunakhod 2 have been reported so far.

The three Apollo reflectors form a large triangle on the lunar surface with sides of 1250, 1100, and 970 km. The complex angular motions of the moon about its center of mass thus can be separated with high accuracy from the range changes due to center-of-mass motion by differential range measurements to the different reflectors. No evidence of degradation with time in the return signals from any of the Apollo reflectors has been observed so far within the observational accuracy of about ±50%, and thus an operational lifetime of at least a decade and possibly much longer is expected.

Range Measurements at McDonald

The 2.7 m telescope at the McDonald Observatory is a general-purpose instrument used in a variety of observational programs. Typically, the measurements of lunar ranges has been scheduled for three observing periods per day, weather permitting, except close to new Moon. One of these observing periods is chosen to be when the moon is near its highest point in the sky, and the others about three hours earlier and later. The total scheduled telescope time for the experiment is about 60 hours per month.

Since 1970 the lunar ranging work at McDonald has been under the direction of E. C. Silverberg. Many improvements in the equipment and experimental techniques, including particularly the telescope guiding, have been made during this period. Both the frequency of successful observations and the accuracy have shown major improvements. The numbers of successful runs per half year, starting from the first half of 1970, have been 7, 55, 83, 160, and 226 respectively. A successful run is defined here as a sequence of perhaps 50 to 300 laser shots, fired over a period of from 50 to 20 minutes, in which a statistically significant number of consistent return signals is obtained.

After the initial acquisitions using the electronic bin system, the electronics at McDonald were put into their originally intended operating mode. The basic electronics system relies on making the time delay measurements in two parts. One is a determination of the integral number of 50 nsec intervals between clock pulses which occur during the roughly 2.4 to 2.7 sec transit time of the laser pulse out to the moon and back. The other consists of making highly accurate vernier measurements of the time delays: 1) between a start pulse generated by the outgoing laser pulse and the first subsequent clock pulse, and 2) between a stop pulse generated by the photomultiplier which receives the returned light collected by the telescope and the following clock pulse. Each vernier circuit works by charging up a capacitor at a known rate during the time interval between the two pulses, and then later measuring the resulting voltage. Such circuits can be calibrated to 0.1 nsec or slightly better accuracy, provided that the shape of the start and stop pulses used in the actual measurements are the same as those used in the calibration. The number of 50 nsec intervals and the readings of the two verniers are written down on magnetic tape after each apparent return observed by the photomultiplier, and these are later combined with the vernier calibrations and accurate clock frequency and epoch information to give the final transit time measurement. In addition, a preliminary time of flight is subtracted from the predicted lunar range to produce range residuals which are subsequently printed out during the observation. If a residual agrees within 5 nsec with a previous residual in the run, a teletype bell rings to indicate a possible successful range measurement.

The laser which has been in use at McDonald since October, 1969 is a four-stage Q-switched ruby laser manufactured by the Korad Corp. After the optical energy in the first stage has built up following the Q-switch, the reflectivity of one mirror is reduced rapidly so that the stored energy is dumped in a single short pulse lasting about 4 nsec. This pulse is then amplified by the other 3 stages, giving an output energy of 3 J at 6943.0 A during routine use. The repetition rate is one pulse every 3 sec, and the laser beam divergence is about 1.2×10^{-3} rad (angular diam.).

Even with a 3 J transmitted pulse and a roughly 2 arc sec transmitted beam divergence, the returned optical pulse obtained with the present McDonald system is small. This is mainly due to the relatively low reflectivity in the red of the aluminum coatings on three of the mirrors in the telescope Coudé system, from each of which the light is reflected twice, and the low transmission of the narrow-band spectral filter which is used to reduce stray light. The probability of more than one photoelectron being ejected from the cathode of the photomultiplier by the returned optical pulse is small, so that the range measurements are normally made using single photoelectron pulses. Under good conditions, such signal pulses are obtained for roughly 20% of the laser shots fired. The statistical fluctuation in the range measurement for a single signal pulse is roughly ±2 nsec due to the laser pulse length and some jitter in the photomultiplier. The statistical uncertainty can be reduced to below 1 nsec by averaging the range residuals over 5 or more returns.

The overall accuracy of range data taken at McDonald between October, 1969 and November, 1971 was limited mainly by uncertainties in the time delays associated with the photodetectors and the electronics. It was believed originally that this uncertainty for the data through December, 1969 could be reduced by later calibrations to less than 2 nsec, but unexpected problems in the early electronics made this impossible. Since March, 1970 the calibration uncertainty normally has been 2 nsec or better. However, on some occasions systematic errors of up to 150 nsec occurred due to triggering of the electronics by noise pulses associated with the laser firing sequence. The electronics calibration systems used during this period were tied together later by comparative measurements made after a calibration procedure accurate to about 1 nsec had been developed.

Since December, 1971 a new calibration system has been in use which usually achieves 0.4 nsec or better accuracy for the overall electronic time delay. In this system a small amount of the outgoing laser pulse is sent to the same photomultiplier which observes the return signal. The light is attenuated so that a photoelectron is produced from the photomultiplier cathode on only one shot in 3 or 4. The time delay between the start pulse to the electronics from a fast photodiode which observes the outgoing laser pulse and the "calibration" pulse from the photomultiplier is measured by exactly the same electronics which normally measures the time delay of the return signal from the moon with respect to the start pulse. By averaging over the roughly 300 to 1000 shots fired during a day's ranging, the average time delay of the calibration pulse can be determined accurately. Subtracting this value from the return signal time delay and adding a geometrical correction to refer the measurement to the axis intersection point of the telescope gives the actual travel time.

The observational process includes no means of discriminating between single photoelectron events caused by real returns and by stray light from the moon or the earth's atmosphere. It is necessary to assume a noise model and apply a statistical filtering technique to separate signal from noise. We assume a Poisson distribution for the noise, and experience confirms that this is a good representation. The observations identified by the filtering process may then be used individually or reduced to one compressed "normal point" per run. Both the unfiltered photoelectron events and the filtered observations are deposited in the National Space Science Data Center on a regular schedule, so that they are available to all interested scientists. In addition, "normal points" representing the filtered returns through 1971 have been submitted for publication.

The uncertainty in the averaged residual for a run is obtained by adding the statistical and electronic correction uncertainties quadratically. The usual overall accuracy obtained since December, 1971 is 1 nsec, with higher accuracy being achieved on occasions when a large number of returns is observed. The uncertainties in the two other known corrections to the observed range are small enough to be neglected at present. These corrections are the atmospheric time delay and the effect of the earth tides on the station position. Polar motion and earth rotation are two of the phenomena to be studied using laser range data, so no allowance for the uncertainty due to these effects is included in the overall range uncertainty.

Results

In this section we give some statistical information regarding the degree of success to date measuring lunar ranges. The project has been in operation for over three years. During the first year only about 45 acquisitions were obtained, as the ranging crew spent much time gaining experience in correcting experimental difficulties. The second year, beginning in September of 1970, saw the onset of rather regular range measurements. The two years following that date will serve for the purpose of characterizing the difficulty of the effort; even though some developments, like the offset guiding and calibration schemes, are still in a state of evolution.

Between September 1, 1970 and August 31, 1972, McDonald attempted to measure 955 lunar ranges on the four lunar corner reflectors (three Apollo and one French/Soviet reflector landed by Luna 17). Of these attempts, measurements of the lunar distance were made on about 684 occasions for a 71% success rate. The following Table gives an individual breakdown of the statistics for each of the Apollo arrays. No successful acquisitions have been made of the reflector on Luna 17.

Individual Ranging Statistics

Array	Number of Attempts	Successful Measurements	Number of Laser Shots	Number of Detected Photoelectrons
Apollo 11 (Landed Aug. '69)	344	232	69375	1941
Luna 17 (Landed Nov. '70)	27	0	6480	0
Apollo 14 (Landed Feb. '71)	228	152	47601	1127
Apollo 15 (Landed Aug. '71)	356	300	53856	2791

The overall statistics regarding relative signal shown in the table above may be somewhat misleading due to the long interval over which they were taken. The experimental technique over the two years improved considerably especially with regard to the guiding. Thus, by the time the Apollo 15 corner reflector landed in August of 1971, the ranging on that site took advantage of the many developments which had initially slowed the early ranging. On the other hand, the Apollo 15 corner reflector was the only one used during periods of marginal seeing or poor transparency, and thus the number of returns would be expected to be somewhat less than otherwise.

In order to get a measure of the relative signal strength between the three Apollo corner reflectors we have gone through the exercise of adding up the parameters for only those runs when at least two of the reflectors was acquired. The following Table gives the results of this tabulation. One can note that the indicated signal strength will be naturally higher in this case both because of the better conditions allowing multiple ranging in the same run as well as the fact that these runs are chronologically later in time. We wish to point out that the number of photons received per shot on the larger versus the two smaller corners is almost exactly in the ratio of 2:1 instead of the 3:1 ratio which the design would indicate. Though this discrepancy has been apparent for some time we have so far not been able to come up with any definite explanation.

Ranging Statistics Under Comparable Conditions

	Number of Laser Shots	Number of Detected Photoelectrons	Signal (Shots/P.E.)
Apollo 15 Array	12,328	1142	10.6
Apollo 11 or Apollo 14 Arrays	18,152	862	21.1

In view of this discrepancy, the returns between the Apollo 15 and Apollo 11 and 14 corner arrays was pursued through a number of other tabulations. The signals from the three Apollo corner arrays were determined at the extremes in the libration patterns, to investigate any possible misalignment of the Apollo 15 reflector. The results indicated no evidence for misalignment. Secondly, the comparative returns were tabulated at large negative hour angles as opposed to large positive hour angles, to see if one of the corners was perhaps preferentially aligned relative to our rotating, outgoing polarization. Thirdly, the return from the arrays was tabulated as a function of lunar age. In each case the performance gain of the Apollo 15 array relative to the others is more nearly equal to two than the designed factor of three. The most obvious possibility, other than the catastrophic one which is that the fold-out wing containing 96 of the 300 cubes came off, to explain such an overall degradation is that the corner array was covered with a fine coating of dust during the takeoff of the Apollo 15 lunar module. In view of the complexity of the experiment, however, and the uncertainty of these statistical studies, I believe one should leave open the possibility of a much more sophisticated explanation.

It should be pointed out that in fact one would have expected the return to be higher than the others by more than the straightforward facts of three as a result of the selection criteria used for the Apollo 15 corner. On March 2, 1971, a meeting was held at Perkin-Elmer where after considerable discussion it was agreed that using solely a corner's interferogram and the corresponding computer analysis, based on RMS fringe line deviation, is not a sufficient nor in fact correct criteria for energy (photons) return. The reason is that the technique does not take into consideration the "rolled" areas around the circumference and adjacent to the edges which is ineffective from the experimentally important standpoint of energy return. Perkin-Elmer agreed to perform an analysis of each of the flight corners and provide a new figure of merit which was a measure of presence of or lack of rolled areas. This new and revealing information was used in selecting which "flight quality" corners were flown in the Apollo 15 array. And as a result, as a group they were 5-10% more efficient than had the interferogram information by itself been employed.

Ranging Accuracy

At the present time we are able to fit the entire data period with residuals of about 2 m. When the solution of the libration equations to high accuracy has been completed, we expect to be able to fit the lunar range data within the combined uncertainty of the measurements and the BIH corrections for polar motion and the rotational position of the earth. The 5 day mean BIH values are currently believed to be accurate to ±40 cm for each component of polar motion and ±0.03 arc sec in angular position. The error in range due to the earth's angular position uncertainty can be as high as 70 cm well before or after meridian passage, so that this may be the dominant error source for many measurements. However, on days when measurements before, during, and after meridian passage are available, the necessary polar motion and earth rotation corrections can be obtained directly from the range data. Measurements on such days, or when the moon is near the zenith, are expected to give the most reliable data for determining the lunar orbit and other information. The entire data set can then be reanalyzed to start obtaining information on polar motion and earth rotation. The ±1 nsec accuracy McDonald data from December, 1971 on will be particularly useful for this purpose. However, data from additional stations will be needed before the results can be anywhere near complete.

New Results from Lunar Range Data

The analysis of the laser lunar range data obtained at the McDonald Observatory is still in its early stages. The accuracy already achieved routinely in lunar laser ranging represents a hundred-fold improvement over any previously available knowledge of the distance to points on the lunar surface. Already, extremely complex structure has been observed in the lunar rotation and significant improvement has been achieved in the lunar orbit. The selenocentric coordinates of the retroreflectors give improved reference points for use in lunar mapping, and new information on the lunar mass distribution has been obtained. However, the history of science shows many cases of previously unknown phenomena discovered as a consequence of major improvements in the accuracy of measurements. It will be interesting to see whether this once again proves the case as we acquire an extended series of lunar distance observations with decimetric and then centrimetric accuracy.

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