Reports

Apollo 11 Laser Ranging Retro-Reflector: Initial Measurements from the McDonald Observatory

Abstract. *Acquisition measurements of the round-trip travel time of light, from the McDonald Observatory to the Laser Ranging Retro-Reflector deployed on the moon by the Apollo 11 astronauts, were made on 20 August and on 3, 4, and 22 September 1969. The uncertainty in the round-trip travel time was ± 15 nanoseconds, with the pulsed ruby laser and timing system used for the acquisition. The uncertainty in later measurements of a planned long-term sequence from this observatory is expected to be an order of magnitude smaller. The successful performance of the retro-reflector at several angles of solar illumination, as well as during and after a lunar night, confirms the prediction of thermal design analyses.*

The Apollo 11 Laser Ranging Retro-Reflector (LRRR) was designed by a team of scientists and engineers to serve as a reference point on the lunar surface to be used in continued monitoring of the point-to-point distances between it and stations on earth by the technique of short-pulse laser ranging. The compact array of 100 fused silica corner reflectors (3.8 cm in diameter) each recessed by one-half its diameter in an aluminum panel, was designed to allow adequate returns during both lunar day and night, thus avoiding systematic gaps in the ranging measurements (*1*). An uncertainty of ±1 nsec in the absolute measurements of the round-trip travel time is possible, based upon experience with current laser and timing techniques. With the above uncertainty in timing (equivalent to ± 15 cm in the one-way distance), suitably corrected for atmospheric delays, much new information on the dynamics of the earth-moon system can be obtained. (The present uncertainty of about 3 parts in 10^7 in the knowledge of the velocity of light will not affect the scientific aims of the experiment, since all measurements will be made in terms of the light second. This is the unit now used to measure distances in the solar system.) Primary scientific objectives include the study of gravitation and relativity (secular variation in the gravitational constant), the physics of the earth (fluctuation in rotation rate, motion rate, motion of the pole, large-scale crustal motions), and the physics of the moon (physical libration, center-of-mass motion, size, and shape) (*2*).

Instrumentation is being developed at the new 107-inch telescope of the McDonald Observatory of the University of Texas (*3*) to permit frequent and long-continued range measurements to the LRRR with the smallest uncertainty allowed by existing technology. This report presents the measurements made with an acquisition system consisting of a Space Rays custom-built, two-stage Q-switched ruby laser (7 joules, 20-nsec pulse length, 2.4×10^{-3} radians full beam divergence from 0.75-inch rod, one pulse every 6 seconds), and the basic digital timing circuits of a system ultimately capable of an accuracy of 1 nsec when vernier time-to-pulse-height converters are added and calibrated (*4*).

The residuals of the round-trip light travel times during acquisition are shown in Table 1. They include the atmospheric index of refraction delay. The round-trip travel time is measured from the intersection of the declination and polar axes of the 107-inch telescope. The LE16 ephemeris of the Jet Propulsion Laboratory was used by J. D. Mulholland in providing the travel time prediction used in the range-gate circuitry. The larger residuals are just at the limit of the uncertainty currently attached to that ephemeris (approximately ± 1 μsec for the round-trip travel time).

The observations show that the LRRR survived two lunar nights satisfactorily, that it performs when at very low temperatures during lunar night, as expected, and that the mounting design works to minimize temperature gradients during the off-axis sun illumination when total internal reflection fails and solar energy is deposited behind the reflectors. The measurements show

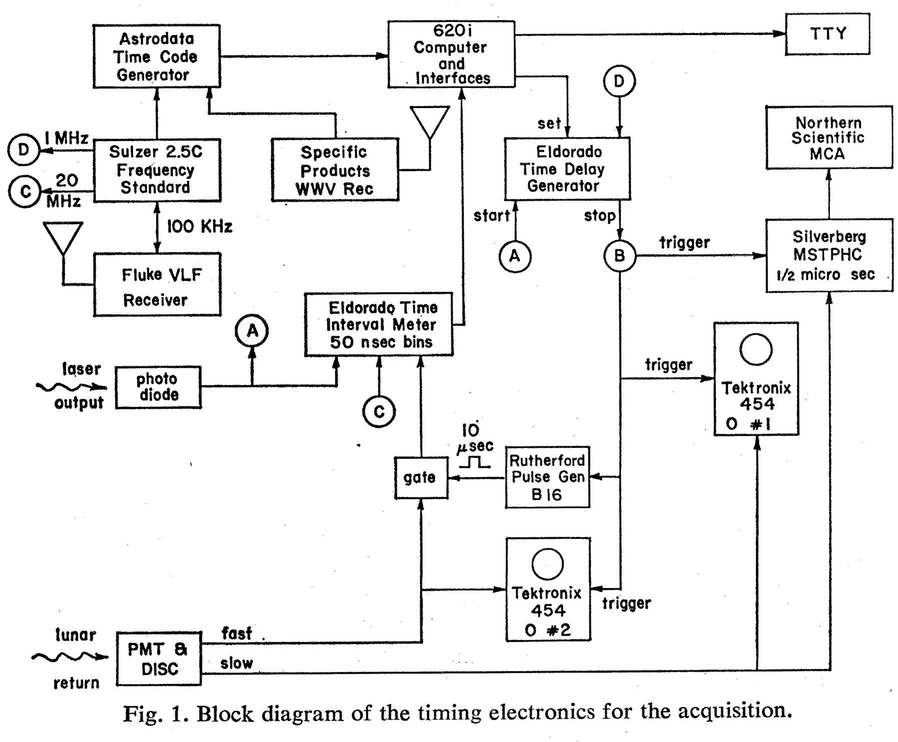

Fig. 1. Block diagram of the timing electronics for the acquisition.

Table 1. Measurements of the round-trip travel time during the acquisition period. The residuals represent the difference between the observed time of travel and that predicted on the basis of the JPL-LE16 ephemeris.

Day	U.T.	Residual travel time (nsec)	Sun illumination for LRRR
20 August	3 : 00	96 ± 15	Sun rising, 21° above eastern horizon
3 September	11 : 10	490 ± 15	Lunar night, sunset terminator 16° to west of Tranquillity Base
4 September	10 : 10	795 ± 24	Lunar night, sunset terminator 27° to west of Tranquillity Base
22 September	4 : 00	−1430 ± 15	Sun approaching lunar noon, 65° above eastern horizon

that the basic computer-controlled timing circuits performed properly. Of particular significance was the pointing of the laser beam to the Tranquillity Base when it was in darkness. The shaft encoders and computer drive of the telescope were used to offset the beam from a visible crater outside the field of view surrounding Tranquillity Base. Observation of LRRR returns demonstrated the initial success of this technique.

A single telescope can be used as a transmitter and a receiver because the large diffraction pattern resulting from the 3.8-cm-diameter corner reflectors (the central spot has a diameter on the earth of approximately 16 km) allows for the velocity-aberration displacement of approximately 1.6 km without significant loss of signal. This was one of the major considerations in the design of the LRRR array. The light travel time of 2.5 seconds between transmitting and receiving allows the mechanical insertion of a mirror that directs the returning photons collected by the telescope into a photomultiplier detector.

The present beam divergence of short-pulse, high-energy ruby lasers requires the use of a large aperture for recollimation so that the beam is narrowed to match the divergence allowed by the atmospheric fluctuations of the index of refraction—typically several seconds of arc. Astronomers refer to this effect as "seeing." The degree of atmospheric turbulence at an observatory at a given time thus determines the size of the laser beam on the lunar surface, producing a spread of approximately 2 km per second of arc.

Techniques for pointing such narrow beams to a specific location on the moon were developed during the successful Surveyor 7 laser-beam-pointing tests (*5*). An argon-ion laser beam was brought to a focus in the telescope focal plane at the moon-image spot that was chosen for illumination. When the laser beam filled the exit pupil of the telescope and matched its *f*-number, the collimated beam was projected to the selected location on the moon and detected by the television camera on Surveyor 7. For the Apollo laser ranging experiment, the beam is matched into the telescope by using a diverging lens, because it is not possible to focus high-power ruby laser beams in air without causing electrical breakdown. The direction of the projected beam is monitored by intercepting a small portion of the beam with corner reflectors mounted on the secondary mirror-support structure. These reflectors return the intercepted light in such a manner that the light is brought to focus, superimposed on the image of the moon, at the spot to which the beam is being sent. A beam splitter coated with a highly damage-resistant, multilayer dielectric coating reflects the laser beam into the telescope and transmits both the image of the moon and the laser light intercepted by the telescope corner reflectors into the guiding system (*6*). This beam splitter is mounted so that it can be rapidly inserted to couple the laser system to the telescope with minimum disturbance to other observers. The laser detector package and interface optics are mounted permanently on an optical bench attached to the south pier of the telescope at a Coudé focus (*f*/33) on the dome floor. The southern part of the dome floor has been enclosed to house the above equipment and the timing electronics.

The detector package (*7*) contained an RCA 31000F photomultiplier that had a measured quantum efficiency of 5 percent at 6943 Å and a dark current of 80,000 count/sec. When cooled by dry ice (as during ranging operations), the dark current was 10,000 count/sec. Spectral filters with widths of 3 and 0.7 Å were available. Both filters were temperature controlled. Pinholes restricting the field of view of the telescope to 6 or 9 seconds of arc were commonly used. An air-driven protective shutter was closed during the time of laser firing, and it was only opened for approximately 1 second around the time for receiveing returns. The net efficiency of the whole receiver (that is, the ratio of the number of

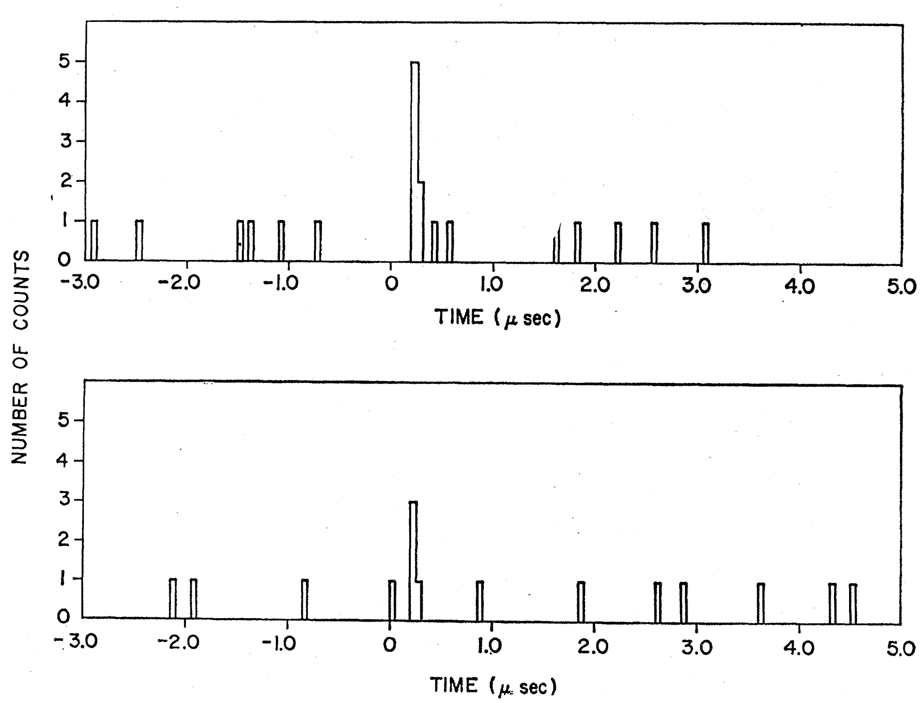

Fig. 2. Histograms of single-stop time-interval-meter readings for two successive 50-shot runs on 20 August 1969. The origin of time indicates the predicted time of return of the reflected signal.

photoelectrons produced to the number of photons entering the telescope aperture) including telescope optics and the 3-Å filter was measured with starlight from Vega and found to be 0.5 percent.

The block diagram of the timing electronics used during the acquisition period is shown in Fig. 1. The electronics consist of a multistop time-to-pulse-height converter (MSTPHC) for coarse range search covering an interval of 30 μsec with 0.5-μsec bins (*8*) in addition to the core circuits forming part of the intended nanosecond timing system (*9*). The initial and final vernier circuits of this system were not in use. The range prediction provided by J. D. Mulholland was recorded on magnetic tape at 6-second intervals. The online computer read the range prediction, set the range-gate time-delay generator (TDG), and fired the laser within 3 μsec of the integral 6-second epoch (*10*). The TDG activated the MSTPHC, triggered a slow-sweep oscilloscope (the display being recorded on photographic film) and a fast-sweep oscilloscope (recorded on Polaroid), and activated a 10-μsec gate into the time-interval meter (TIM). The computer read the number of counts in the TIM and calculated the difference between this reading and the range prediction, printing out this difference on the teletypewriter to the nearest nanosecond. The MSTPHC range accuracy depended on the TDG, whereas the TIM range accuracy is entirely independent of the TDG.

The first high-confidence-level return was recorded for a 50-shot run at approximately 2:50 U.T. on 20 August 1969. A part of the TIM printouts is displayed as a histogram in Fig. 2. Here, the origin of the time axis is at the predicted range. The lower histogram shows a portion of the printouts for a 50-shot run taken a few minutes later in which a 5-μsec internal delay was introduced. (This delay has been subtracted in the drawing.) Noise scans in which the laser was fired into a calorimeter displayed no buildup. Four other scans recording signals were made in the 50 minutes before the moon sank too low in the sky. Operation earlier in the night had been prevented by cloud cover.

The randomness of the difference between the TIM printout with a resolution of 1 nsec and the ephemeris prediction enabled a statistical reduction of the data even without the vernier circuits designed to interpolate between the 50-nsec digital intervals. The result is a measured round-trip travel time in excess of the Mulholland prediction by 96 ± 15 nsec of time at 3:00 G.M.T., 20 August 1969, from the intersection of the declination and polar axes of the 107-inch telescope. The uncertainty corresponds to $\pm$ 2.5 m in one-way distance.

The size of the measured return signals is consistent with the maximum differential backscattering cross section of the LRRR of 5×10^{11} cm^2/steradian for on-axis illumination, including the effect of the velocity aberration when the cross section is corrected for off-axis angles produced by optical librations and for temperature gradient distortions (calculated). This correction amounted to a reduction in the above cross section by a factor 0.2 for the 20 August observation. (This factor has a calculated range from 0.2 to 0.9.) The "seeing" on 20 August was estimated to be 4 seconds of arc, which, when combined quadratically with the telescope beam divergence of 3 seconds of arc, produced a root-mean-square outgoing beam of 5 seconds of arc. When a telescope transmission of factor 0.3 and an atmospheric transmission of factor 0.7 are used along with the measured receiver efficiency of 0.5 percent mentioned above, a return of one photoelectron detected in seven shots is predicted, in agreement with the upper histogram in Fig. 2. Although the signal is small, the background noise level (with the 0.7-Å filter) is such that there is high confidence in the detection. This confidence is due to the steadiness of the range prediction for short times and to the prompt return of photons from the LRRR; this prompt return causes the signal photoelectrons to cluster in time relative to the predictions, in contrast to the random occurrence of background pulses.

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10. J. D. Rayner, *A Description of the Control Program for the Lunar Ranging Experiment* (University of Maryland Department of Physics and Astronomy Technical Report No. 70–064, November 1969).
11. This experiment is being supported by NASA. Formal responsibility has rested with the following group: Principal Investigator, C. O. Alley (University of Maryland); Co-Investigators: P. L. Bender (National Bureau of Standards), R. H. Dicke (Princeton University), J. E. Faller (Wesleyan University), W. M. Kaula (University of California at Los Angeles), G. J. F. MacDonald (University of California at Santa Barbara), J. D. Mulholland (Jet Propulsion Laboratory), H. H. Plotkin (NASA Goddard Space Flight Center), and D. T. Wilkinson (Princeton University); Participating Scientists: W. Carrion (NASA Goddard Space Flight Center), R. F. Chang (University of Maryland), D. G. Currie (University of Maryland), and S. K. Poultney (University of Maryland). Responsibility for the detailed design of the LRRR to perform continuously in the lunar environment has been carried primarily by J. E. Faller, D. G. Currie, R. F. Chang, and C. O. Alley, supported by the following engineering companies: Arthur D. Little, Inc. (P. Glaser, J. Burke, F. Gabron, and D. Comstock); The Perkin-Elmer Corporation (J. Atwood, P. Forman, G. Watt, and S. Lauffer); and the Bendix Aerospace Corporation (C. Weatherred, R. Hill, J. Brueger, R. Woolford, and K. Moore).
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