Laser Ranging Retro-Reflector: Continuing Measurements and Expected Results

Abstract. *After successful acquisition in August of reflected ruby laser pulses from the Apollo 11 laser ranging retro-reflector (LRRR) with the telescopes at the Lick and McDonald observatories, repeated measurements of the round-trip travel time of light have been made from the McDonald Observatory in September with an equivalent range precision of ±2.5 meters. These acquisition period observations demonstrated the performance of the LRRR through lunar night and during sunlit conditions on the moon. Instrumentation activated at the McDonald Observatory in October has yielded a precision of ±0.3 meter, and improvement to ± 0.15 meter is expected shortly. Continued monitoring of the changes in the earth-moon distance as measured by the round-trip travel time of light from suitably distributed earth stations is expected to contribute to our knowledge of the earth-moon system.*

The performance (*1*) of the Apollo 11 laser ranging retro-reflector (LRRR) left on the moon, as well as that of the instrumentation at the ground observatories, has been in accord with the original expectations (*2–5*). The scientific objectives are such that lengthy analysis of a long-continuing series of frequent measurements is required before results are available. The experiment had its origin in discussions among members of the experimental gravitational research group at Princeton University (*6*). Because of the many areas of science and technology involved in the experiment, a group (*7*) was organized to carry it out.

The compact array of high-precision optical retro-reflectors (cube corners) deployed on the moon (*1, 8*) is intended to serve as a reference point in measuring precise ranges between the array and points on the earth by using the technique of short-pulse laser ranging. The atmospheric fluctuations in the index of refraction diverge a laser beam and prevent the spot on the moon from being smaller than approximately 1.6 km in diameter. The curvature of the lunar surface results in part of the short pulse being reflected before the rest, producing a reflected pulse measured in microseconds, even if the incident pulse is measured in nanoseconds. The retro-reflector array eliminates this spreading because of the small size of the array. (The maximum spreading of a pulse because of optical libration tipping of the array will be approximately ± 0.125 nsec.) In addition, the retro-reflective property causes a much larger amount of light to be directed back to the telescope from the array than is reflected from the entire surface area illuminated by the laser beam.

The basic uncertainty in measuring the approximately 2.5-sec round-trip travel time is associated with the performance of photomultipliers at the single photoelectron level. This uncertainty is estimated to be approximately 1 nsec. When the entire system is calibrated and the effects of the atmospheric delay are calculated from local temperature, pressure, and humidity measurements and subtracted from the travel time, where the uncertainty in this correction is estimated to be less than 0.5 nsec, an overall uncertainty of ± 15 cm in one-way range seems achievable.

The present uncertainty of three parts in 10^7 in the knowledge of the velocity of light will not affect the scientific aims of the experiment, since it is the practice to measure astronomical distances in light travel time. 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 of the pole, large-scale crustal motions), and the physics of the moon (physical librations, center-of-mass motion, size, and shape) (*2–5*). Estimates of improvements expected in some of these categories are shown in Tables 1 to 3. The estimated uncertainty for each quantity is intended to be an upper limit.

Reflected signals from the LRRR were acquired 1 August (and 3 August, with a different laser system) with the 120-inch telescope of the Lick Observatory (*9*) at Mt. Hamilton, California, and 20 August with the 107-inch tele-

Table 1. Lunar orbital data parameters.

Quantity	Present uncertainty (approximate)	0.15-m Range accuracy*	
		Uncertainty	Time (yr)
Mean distance	500 m	25 m	1
Eccentricity	1×10^{-7}	4×10^{-9}	1
Angular position of Moon			
With respect to perigee	2×10^{-6} rad	4×10^{-8} rad	1
With respect to Sun	5×10^{-7} rad	4×10^{-8} rad	1
Time necessary to check predictions of Brans-Dicke scalar-tensor gravitational theory			8

* Three observing stations.

Table 2. Lunar libration and relation of LRRR to center of mass.

Quantity	Present uncertainty (approximate)	1.5-m Range accuracy*	
		Uncertainty	Time (yr)
Libration parameters†			
$\beta = (C-A)/B$†	1×10^{-5}	3×10^{-8}	4
$\gamma = (B-A)/C$	5×10^{-5}	2×10^{-7}	1.5
Coordinates of LRRR with respect to center of mass‡			
X_1	500 m	25 m	1
X_2	200 m	7 m	1
X_3	200 m	5 m	3

* Three observing stations are assumed. † *A* is the moment of inertia about the principal axis toward the earth, *B* is the moment about the principal axis tangent to the orbit, and *C* is the moment about the moon's rotation axis. Knowledge of the parameters β and γ is important in determining the mass distribution within the moon. ‡ X_1, X_2, and X_3 are measured along the principal axes about which the moments *A*, *B*, and *C* are defined.

Table 3. Geophysical data determinable from LRRR.

Quantity	Present uncertainty (estimated)	0.15-m Range accuracy
Rotation period of earth (sec)	5×10^{-3}	1×10^{-3}
Distance of station from axis of rotation (m)	10	0.3
Distance of station from equatorial plane (m)*	20	0.6 to 2†
Motion of the pole (m)*	1 to 2	0.15
East-west continental drift rate observable in 5 years (cm/yr)*	30 to 60	3
Time for observing predicted drift of 10 cm/yr of Hawaii toward Japan (years)	15 to 30	1.5

* Three or more observing stations are required. † Depending upon the latitude of the station.

Table 4. Measurements at the McDonald Observatory of round-trip travel time during acquisition. 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 round-trip travel time (nsec)
20 August	03:00	96 ± 15
3 September	11:10	490 ± 15
4 September	10:10	795 ± 24
22 September	04:00	−1430 ± 15
17 October	01:44	−798 ± 15*
18 October	01:17	−978 ± 15*
1 November	11:40	−2034 ± 15*
16 December	01:45	1232 ± 15*

* The present accuracy is ±15 nsec in the knowledge of the electronic time delays. Upon completion of the current calibration, the accuracy will be determined by the present overall resolution, less than ±2 nsec, limited by the laser pulse length and photomultiplier jitter.

scope of the McDonald Observatory (*10*) at Mt. Locke, Texas. These observations showed that the LRRR did not suffer any major degradation, if any at all, from debris generated during lift-off of the lunar module. The signals are consistent with the return expected from the LRRR design, within the uncertainties of atmospheric "seeing," telescope transmission, and other optical losses. Continued acquisition period measurements at McDonald in September (*10*), taken with the initial observations, have demonstrated the successful performance of the LRRR at several sun illumination angles, as well as during and after a lunar night, confirming the prediction of thermal design analyses.

A first "geodetic result" from the acquisition observations at Lick (*9*) was the discovery, from the drift of the residual round-trip travel time with respect to the JPL lunar ephemeris 16 (LE16) predictions, that the coordinates for the 120-inch telescope are not those given for Mt. Hamilton (Lick Observatory) in the *American Ephemeris and Nautical Almanac* (*9a*). The Lick Observatory participated in the acquisition phase of the experiment to increase the probability of getting early returns. The weather and seeing are generally excellent there in the summer. Laser ranging activities ceased at Lick in August.

In October a custom-built four-stage ruby laser, made by Korad, was installed at the McDonald Observatory. This laser was built to specifications developed for long-term precision measurements in the lunar ranging experiment. The pulse length is produced by a time-varying reflectivity mode of operation and can be as short as 2.8 nsec, although a more typical value is 4 nsec. It transmits 5 joules with a beam divergence (full width) of 1.4 mradian at a repetition rate capability of one shot every 3 seconds. At the same time, vernier timing circuits (*11–13*) shown schematically in Fig. 1 were activated. This instrumentation allows a resolution uncertainty of ±2 nsec on each measured return. The accuracy depends on thorough calibration of all electronic delays. This will be completed soon to the 1-nsec level. The measurements made in October, November, and December, and which are shown in Table 4, still have a calibration uncertainty in accuracy of ±15 nsec. These later measurements are subject to reduction of the accuracy uncertainty upon completion of the final calibration.

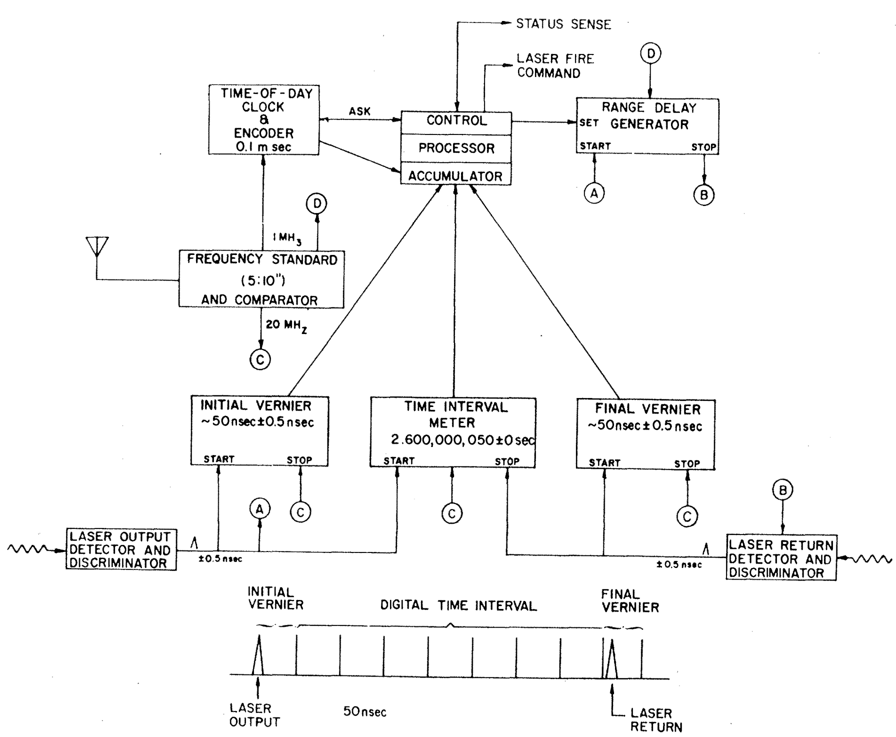

Fig. 1. Representation of the nanosecond-resolution time-interval measurement system now in use at the McDonald Observatory. Special circuits eliminate any ±1 count uncertainty in the 20-Mhz, digitally measured interval. The vernier components are time to pulse height converters.

As more experience is gained in the use of the new 107-inch McDonald telescope, the goal is three measurement periods daily. Each period would last about 15 minutes, enabling several hundred laser shots to be fired; the periods would be scheduled near the time of meridian crossing, several hours before, and several hours after.

From these measurements, one can obtain the minimum range and its epoch of occurrence. Harmonic analysis of this range time series will permit the determination of the qualities listed in Tables 1 through 3.

In order to satisfy all the scientific aims of the experiment, it is hoped that more U.S. and foreign ground stations can be established to carry out regular precision ranging to the LRRR. The deployment of several more LRRR's on the moon would allow a more detailed study of the lunar physical librations, independent of any model. One of these should be designed to give a larger return than the Apollo 11 LRRR, so as to allow participation in the ranging program by smaller telescopes.

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7. 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).
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