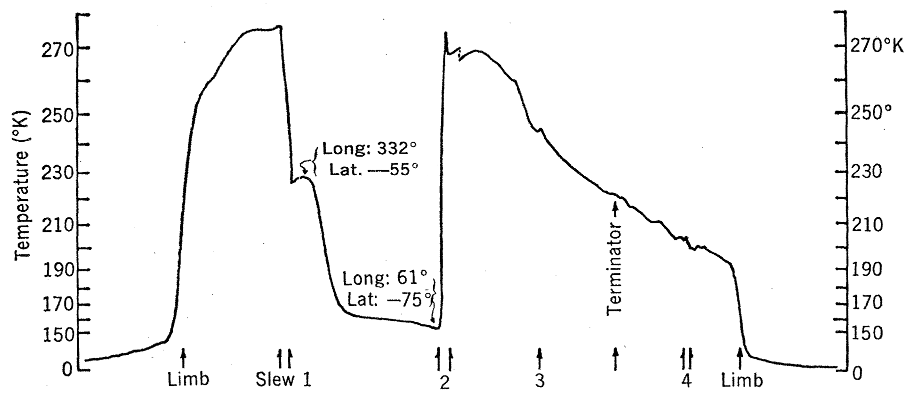

Fig. 2. Temperatures measured in channel 2 (18 to 25 μm) of the infrared radiometer in Mariner 7 during near encounter, in a scale proportional to energy. The times when the platform was slewed and the crossing of prominent planetary features are indicated. The extreme planetocentric coordinates of the swath through the polar cap are also shown.

significant response to off-axis sources. For example, the response of channel 2 of the radiometer aboard Mariner 7 to a point source at a distance of 12 degrees from axis was only 0.3 percent of that for the same source on axis. Because of the large solid angles subtended, however, the extended wings beyond a central area 1 degree in diameter contributed 27 percent of the total response of a measurement of the energy radiated by an isothermal source filling the entire object space. The correction to the minimum temperature measured in Mariner 7, due to the extended response of channel 2 and based on a model temperature distribution over the planetary surface, amounts to about —3°K. At low temperatures, the correction for off-axis radiation was greater for channel 1 than for channel 2. A more refined analysis of the systematic effects, based on data obtained before near encounter and during passage across the limb, is in process. All systematic errors that have been thought of, however, have the effect that the observed temperatures are higher than the true value.

The Mariner flights provided the opportunity to measure temperatures with an areal resolution approximately ten times that obtainable from the earth. Although transitions between dark (maria) and light (desert) areas appear well defined in the data, there were no sharp changes in temperature exceeding 1°K in contiguous fields of view (50 km at closest approach). The only sharp temperature fluctuation which does not seem to be associated with any feature in the "classical" maps of Mars was recorded in both channels of Mariner 6 at longitude 307.0° and latitude —3.5°, identified in Fig. 1. The TV pictures of this area show a complex terrain structure that may be related to this temperature anomaly (*5*).

Because the track of Mariner 6 was nearly equatorial (*3*) and extended well beyond the terminator, it is particularly suited for a determination of the parameters characterizing the gross thermophysical properties of the martian ground. The cooling curve of a homogeneous solid with $(K\rho c)^{1/2} = 4 \times 10^{-3}$ cal/cm^2 sec$^{1/2}$ per degree Kelvin, where K is heat conductivity, ρ is density, c is specific heat, and albedo of 0.85, fits the measurements quite well, although obvious departures are noticeable in Fig. 1. This result agrees with the general conclusions of Sinton and Strong (*6*). Our results should be considered tentative, although we believe that a more detailed analysis of the data will not change the conclusions significantly. A thorough analysis of the systematic effects present in the data is underway; a correlation with the results of the television and infrared spectrometer experiments is planned.

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5. We thank R. B. Leighton and the entire Mariner 69 TV team for allowing us to see their pictures before publication and for their valuable comments.
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7. Many persons within the Mariner 1969 Project contributed to the success of this experiment, but our special thanks are due to H. Schurmeier, J. Stallkamp, and C. Kohlhase for their efforts on our behalf. We also thank J. Bennett and D. Griffith for help in the acquisition and reduction of the data.

9 September 1969

Laser Beam Directed at the Lunar Retro-Reflector Array: Observations of the First Returns

Abstract. *On 1 August between 10:15 and 12:50 Universal Time, with the Lick Observatory 120-inch (304-cm) telescope and a laser operating at 6943 angstroms, return signals from an optical retro-reflector array placed on the moon by the Apollo 11 astronauts were successfully detected. After the return signal was first detected it continued to appear with the expected time delay for the remainder of the night. The observed range is in excellent agreement with the predicted ephemeris. Transmitting between 7 and 8 joules per pulse, we found that each return signal averaged more than one photoelectron. This is in good agreement with calculations of the expected signal strength.*

One of the scientific instrument packages placed on the moon by the Apollo 11 astronauts is an array of optical retro-reflectors whose purpose is to permit short-pulse laser ranging from stations on the earth (*1*). The retro-reflector array, for which one of us (J.E.F.) provided the basic design, consists of 100 fused silica corner cubes each 3.8 cm in diameter mounted in an aluminum panel 46 by 46 cm. The reflectors, which have a life expectancy in excess of 10 years, are designed to perform under essentially isothermal conditions throughout lunar night and most of the lunar day. The retro-reflector package on the lunar surface eliminates the stretching in time of the return signal which would otherwise be produced by the curvature and irregularity of the

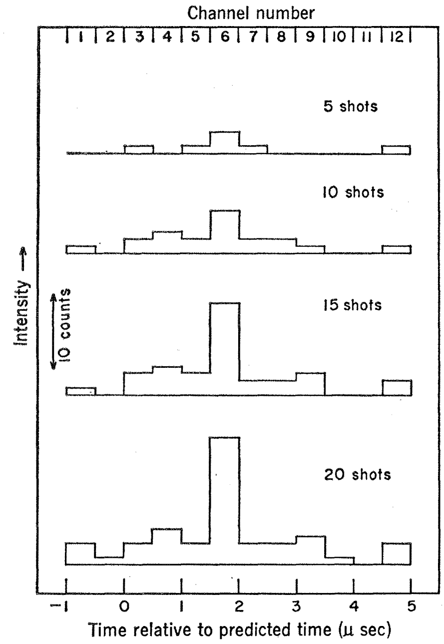

Fig. 1. A histogram showing the growth of the retro-reflected signal in channel number 6.

moon's surface. As a result point-to-point measurements of the distance can now be made with an accuracy approaching 15 cm. Over a period of years, distance measurements to this accuracy will permit precise measurements of the lunar orbital motion, lunar librations, the lunar radius, fluctuations in the earth's rotation rate, Chandler wobble of the earth's axis, intercontinental drift rate, and a possible secular change of the gravitational constant.

A number of stations have been established in the United States for the purpose of ranging with lasers to the retro-reflector array. We report here the first successful observation of a return signal which was made with the 304-cm telescope at Lick Observatory. This telescope was specifically instrumented, and telescope time was made available for the purpose of assisting NASA in acquiring reflected signals from the array.

Lick's early acquisition is expected to aid other stations in acquiring the retro-reflector signal since it eliminates the need for them to perform any extended search in either position or range. It also showed that the array has successfully survived the returning module's blast-off; the fact that the signal strength agrees with estimates based on the overall efficiency of the system confirms both that the condition of the array is satisfactory and that its operation on the lunar surface is as expected.

The ranging system at Lick consisted of a giant-pulse, high-powered ruby laser operated at the coudé focus which was optically coupled through the 304-cm telescope and could be fired at 30-second intervals. The angular diameter of the outgoing beam was approximately 2 seconds of arc and made a spot of light on the moon about 3.2 km in diameter. The return signal was detected by a photomultiplier that was mounted at the coudé focus behind a 10 arc-second field stop and a narrow (0.7 Å) filter which were used to reduce the background illumination from the sunlit moon. A time-delay generator, initiated by the firing of the laser, was used to activate the acquiring electronics some 2½ seconds (the earth-moon round-trip time for light) later. The delay generator was set for each shot with an ephemeris provided by Dr. J. D. Mulholland.

Following the pulse produced by the delay generator, the output pulses from the photomultiplier were channeled sequentially into 12 binary scalers with a dwell time for each scaler channel that was adjustable from ¼ to 4 μsec. The routing of the pulses to the scalers was such that a pulse arriving within 0.1 μsec of the end of a channel would also add a count to the following channel. The contents of the scalers then contained a quantized summary of the detector output for a short time interval centered on the expected arrival time of the reflected signal. After each cycling of the scalers that followed a laser firing, a small on-line computer read their contents and reset them. The computer was used to store the accumulated count for each of the scalers, and provided a printed output and a cathode-ray tube display of the data.

Scattered sunlight from the lunar surface produced a random background that slowly filled the 12 time channels. Because the return from the retro-

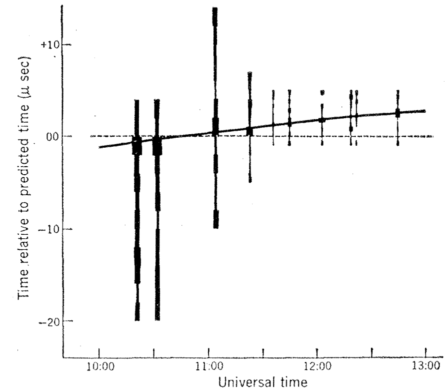

Fig. 2. A three-dimensional figure showing the time of the run (abscissa), the range window during which the equipment was open for receiving data (ordinate), and the number of counts in each channel (width of the bar). In each run in which returns were expected they were seen in the correct channel. During run number 19 (3rd from right-hand end) the telescope was pointed away from the reflector, and no returns were seen.

Table 1. Log of observational data showing acquisition.

Run No.	Total counts in channel number												No. of shots	Time (U.T.)	Channel width (μsec)	Time of 1st channel (μsec)
	1	2	3	4	5	6	7	8	9	10	11	12				
10	12	8	16	18	12	14	10	17	13	**27**	12	12	20	1021	2.0	−20
11	12	12	12	11	11	6	13	11	14	**26**	10	14	14	1032	2.0	−20
12	Data invalidated by range-gate errors												16		2.0	−10
13	13	8	8	12	7	**18**	11	5	6	7	8	12	13	1104	2.0	−10
14	Data invalidated by range-gate errors												6		1.0	−10
15*	4	3	3	5	4	**17**	6	8	10	5	6	8	18	1123	1.0	−5
16	1	1	2	2	**6**	3	3	1	2	1	3	2	10	1136	0.5	−1
17	6	3	4	2	**11**	**9**	2	7	2	4	2	5	16	1145	0.5	−1
18	3	1	3	5	3	**19**	3	3	4	1	0	4	22	1203	0.5	−1
19†	3	3	3	10	4	3	5	2	5	5	8	5	22	1219	0.5	−1
20‡	2	1	1	0	3	4	**6**	2	4	2	2	4	10	1223	0.5	−1
21	5	2	2	3	2	1	**12**	**11**	3	4	5	2	22	1245	0.5	−1

* Data from three shots with erroneous range gates deleted from tabulation. † Telescope pointed 16 km south of reflector. ‡ Thin clouds noted near moon.

reflector occurred with a predetermined delay, the channel corresponding in time to the arrival of the signal accumulated data at a faster rate than the other 11 channels. Figure 1 illustrates this point by showing the way the data actually accumulated during one of the runs (number 18). Throughout this report original data is given; a number of small corrections (instrumental and atmospheric) would need to be made before converting to an actual range.

On the night of 1 August a total of 169 shots were fired following acquisition. Range-gate errors occurred on 27 shots, and 22 shots were fired with the telescope pointed away from the reflector. For the remaining 120 shots approximately 100 above-background counts were received. This represents a return expectation in excess of 80 percent and shows that all parts of the experiment were operating satisfactorily. Assuming a Poisson distribution of the recorded photoelectrons, we find that this corresponds to an average of 1.6 detectable photoelectrons per shot. This number is a lower limit to the true average since interference effects as well as guiding errors can be expected to have reduced the number of returns that were recorded. The strength of this signal and the lack of "spill" into adjacent channels clearly shows that the signal did not come from the "natural" lunar surface, the return from which would be distributed over about 8 μsec. The timing of the trigger from the delay generator relative to Mulholland's ephemeris was changed three times and the channel widths were decreased from 2 to 1 and then ½ μsec. After each change, the signal appeared in the appropriate channel. Table 1 gives the data from runs 10 through 21, the interval from the first acquisition to the close of operation. (Nine runs containing 162 shots were made before acquisition.) Column 1 gives the run number, columns 2 through 13 the number of recorded counts in each channel, column 14 the total number of shots fired during the run, column 15 gives the universal time for the middle of the run, column 16 gives the channel width, and column 17 gives the starting time of the 1st channel with respect to the ephemeris predictions. The channel in which the return was expected is printed in boldface.

Figure 2 shows a plot of the data taken from Table 1. Runs 12 and 14 have not been plotted in Fig. 2 because errors in setting the delay generator

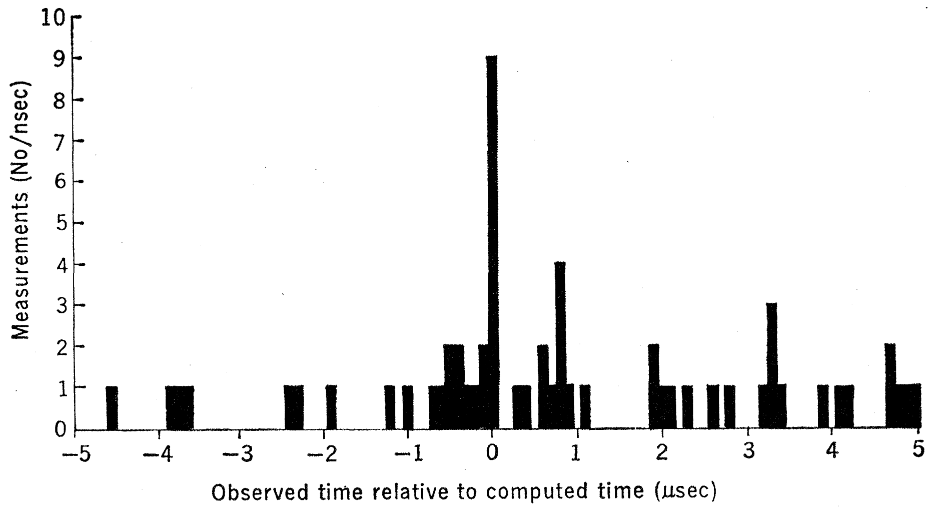

Fig. 3. The number of coincidences in 100-nsec intervals observed on the night of 3 August.

invalidated the timing. During run 19 the telescope was not pointed at the reflector and no returns were seen. Because of a fortuitous splitting of the return between two channels on two of the runs, an effective timing precision of 0.1 μsec was achieved. This is equivalent to a range error of about 15 m. Clearly seen in Fig. 2 is an apparent drift in the time the returns were detected relative to Mulholland's predictions. Although this drift was puzzling at first, we soon realized that it was caused by the fact that the 304-cm telescope is located approximately 500 m east of the location given in *The American Ephemeris and Nautical Almanac* for Lick Observatory. A curve showing this correction to the original ephemeris is given in Fig. 2. Translation of this curve along the ordinate is allowable, and the amount gives the difference between the observed range and the predicted range. It may be seen that the observations agree well with the predicted curve using the correct coordinates.

Two nights after the initial acquisition, a laser with a high repetition rate and a digital time interval measuring system was used to record the range to the retro-reflector. The laser system operated once every 3 seconds with a pulse duration of 60 nsec, full width at half maximum intensity. The detection system consisted of two photomultipliers arranged to detect photoelectron coincidences within a resolution of 60 nsec. The range measurement was made with a standard interval counter with a resolution of 1 nsec, started by a sample of the transmitted energy and stopped by the output of the coincidence detection system. A range-gating pulse was derived from a programmed delay generator.

Over a period of 1 hour and 45 minutes on the morning of 3 August the laser was fired 1230 times. The total number of measured range times during this period was 98. The low number of coincidences can be partially attributed to a possible slight misalignment in the detector optical system and a malfunction of the delay pulse generator. Furthermore, since returns were not immediately recognized, an angle search was instituted during which the signal image was not centered in the coincidence area for relatively long times.

The number of observed coincidences was consistent with that expected from lunar surface reflections and random noise sources. However, retro-reflector returns should occur within 100 nsec of the true range. The observed measurements were therefore compared to the predicted range ephemeris and then linearly corrected because of the range parallax mentioned previously. The technique involved taking the initial range residuals and fitting to a first-order polynomial. The residuals falling within a certain range with respect to the polynomial were then used in redefining the polynomial until a significant number of points occurred within the expected precision of the system. After two repetitions, 11 points were left with a root-mean-square of 45 nsec about the new polynomial. The coefficients of this polynomial agree with expected deviations from predicted range due to the displacement of site location.

Range residuals corrected to this equation in time were then used to construct a histogram (Fig. 3) with 100 nsec intervals from -5 to $+5$ μsec. No data lying outside of ± 5 μsec were plotted since no 100 nsec intervals outside this range contained more than one point. The central 100-nsec interval contains nine points with an r.m.s. of 35 nsec. Because the probability of noise or lunar surface returns occurring at these rates within a given 100 nsec time interval is so low, it can be concluded with a high degree of confidence that the observed signals within this interval are indeed from the retro-reflector package. The uncertainty of ± 7.5 m in the range obtained on the night of 1 August can therefore be improved to ± 5 m by the results obtained on the night of 3 August.

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2 September 1969

Age of the Bay of Biscay: Evidence from Seismic Profiles and Bottom Samples

Abstract. *Paleomagnetic data and marine magnetic surveys suggest that the Bay of Biscay was created by rifting due to an anticlockwise rotation of the Iberian peninsula. The period during which movement occurred is not known precisely, but a rotation, amounting to 22 degrees, appears to have taken place in post-Eocene time. To provide independent evidence on the age of the rift, bottom samples from the Biscay abyssal plain have been related to the distribution of seismic reflectors within the sediments. The investigation shows that a large part of the Bay of Biscay was in existence in late Cretaceous times and that the data can be interpreted in terms of some early Tertiary rotation. However, the amount of possible Tertiary opening is appreciably less than the paleomagnetic results suggest. In view of the fact that reflectors of Middle-Upper Miocene age can be traced as undisturbed horizons across the bay, all tectonic movements must have ceased by the early Miocene.*

The hypothesis, put forward by Wegener (*1*) and others, that the Bay of Biscay formed as a result of an anticlockwise rotation of the Iberian peninsula relative to the rest of Europe has recently received some support from paleomagnetic studies (*2–5*) and from the fanlike pattern of linear magnetic anomalies between the French and Spanish continental slopes (*6*). Girdler (*2*) found a consistent difference of 38° (± 16°) in the declinations in rocks of Permian, Triassic, and early Jurassic age from north and south of the Pyrenees, which can be accounted for by a 40° rotation of Iberia in late Mesozoic and Tertiary time about a point near 44°N, 1°W. According to bathymetric charts, this same amount of movement is necessary to open up the Bay of Biscay, if the 500-fathom (900-m) contour is taken as the boundary between ocean and continent. There is some area of overlap in fitting northern Spain against France in the eastern part of the bay, but this is probably due to outbuilding of the French continental slope by thick accumulations of sediment deposited during the Tertiary (*7*).

The paleomagnetic data of Van Dongen (*3*) and Van der Voo (*4*) based on measurements made in Spain indicate a similar amount of rotation. The former, working with rocks from the eastern Pyrenees, proposed a 30° rotation after Permian time, whereas the latter, using observations from the Meseta, advocated a post-Triassic movement. Watkins and Richardson (*5*) have examined some late Eocene volcanic rocks near Lisbon and have suggested that the Bay of Biscay was partially open during the Eocene and that a 22° rotation occurred sometime later in the Tertiary.

In view of these conclusions, particularly those of Watkins and Richardson which imply that the bay is of fairly recent origin, it seems appropriate to consider some results of a study of the stratigraphy of the sediments of the abyssal plain which forms the floor of much of the Bay of Biscay. We have examined the relation of some cores and dredge samples to several hundred kilometers of seismic reflection profiles, recorded with an air-gun profiler (*8*), in order to determine the age of various parts of the abyssal plain sediments and thus to provide some independent evidence on the age of the Bay of Biscay. The positions of the seismic lines are indicated in Fig. 1. Figure 2 shows the locations and ages of bottom samples, both published (*9–11*) and unpublished (*12*, *13*), from the plain and continental slope.

The reflection records indicate that the sediments of the abyssal plain are well stratified and that they are probably composed of many turbidite layers interbedded with finer-grained material, an assumption strongly supported by the core data and by the pronounced leveling effect of sedimentation close to small seamounts (Fig. 3). We have divided the sequence into three units which can be recognized over a wide area. The uppermost section (the upper turbidites) is about 300 m thick and is made up of many closely spaced reflectors. The middle "homogeneous zone" is approximately 200 m thick and generally lacks strong reflectors in the frequency range in which the recordings were made (60 to 150 cycles per second); this suggests that the sediments are more lithologically uniform than those above and below. The lowest formation (the lower turbidites) is primarily composed of several closely spaced strong reflectors.

A reflector marking the top of a succession of stratified sediments clearly