

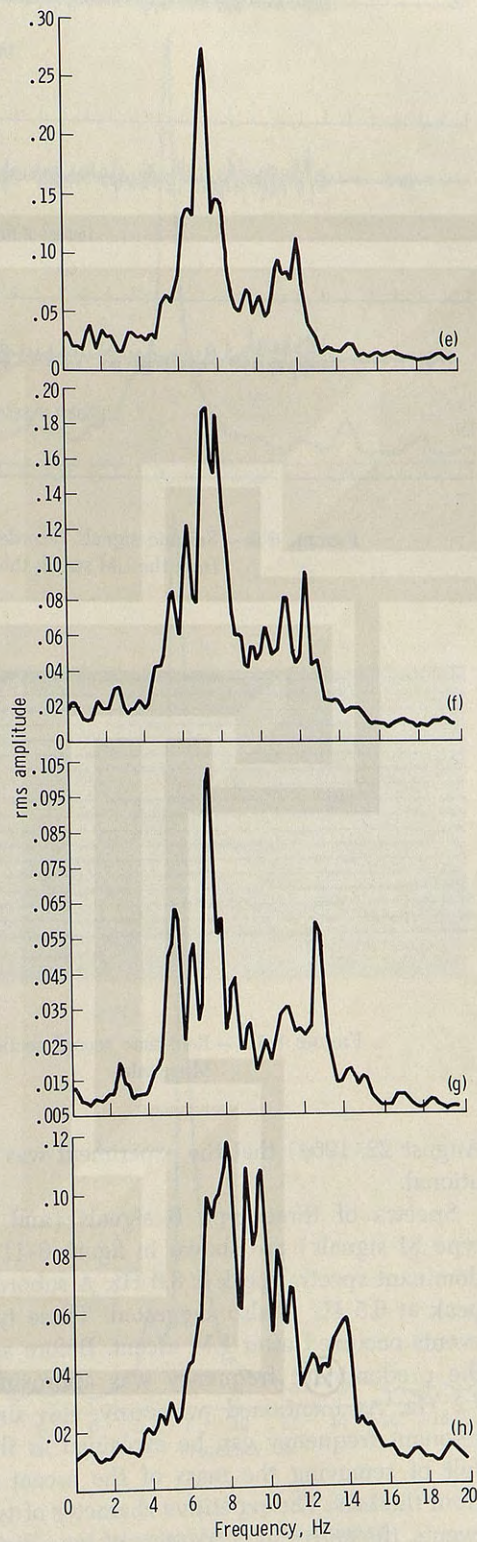
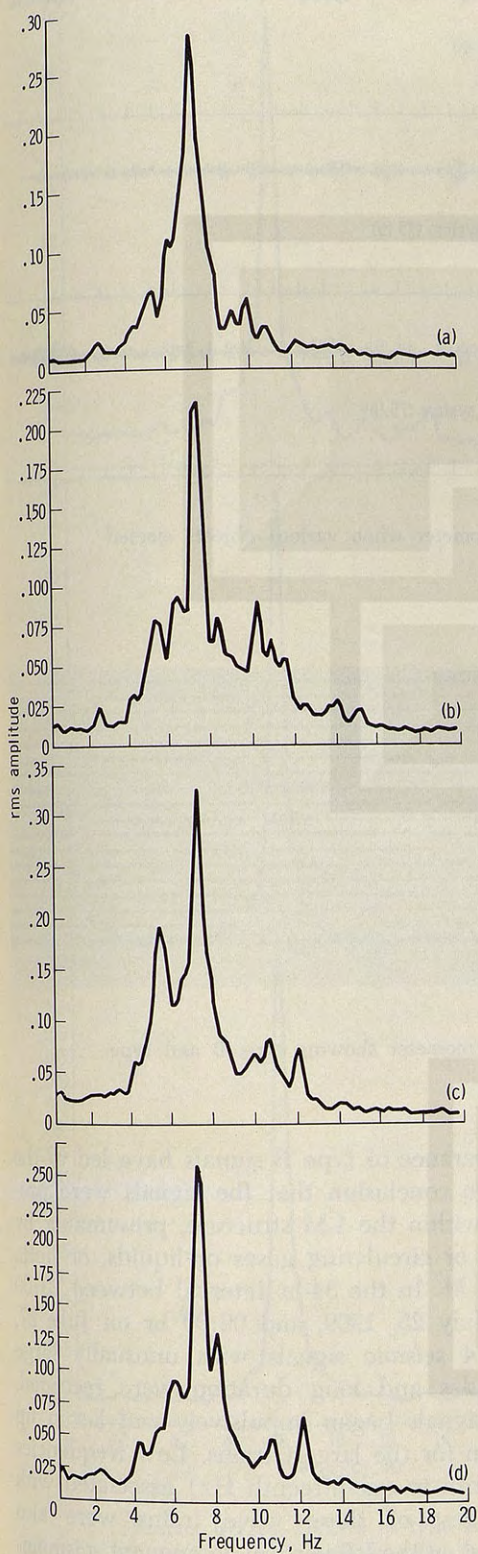
the LM.

the LM.

comparison with active seismic experiment. The physical contact of sample (h) was strong was collected. The content of the seismicity of the seismometer at higher frequencies is greater for the other samples. The frequency range can thus be determined. It falls on the lunar

as turned on, type of amplitudes were present. The signals were recorded. The period of 8 days, completely on July 29, of approximately the initial stages are shown in figures of the record that were recorded during. After a puzzling pattern, the signals became identical structure. The interval between events is approximately 30 sec near the end of the lunar day. The signals reappeared for the second lunar day, from 09:00 to 02:00 hr on

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 (e) impact of the
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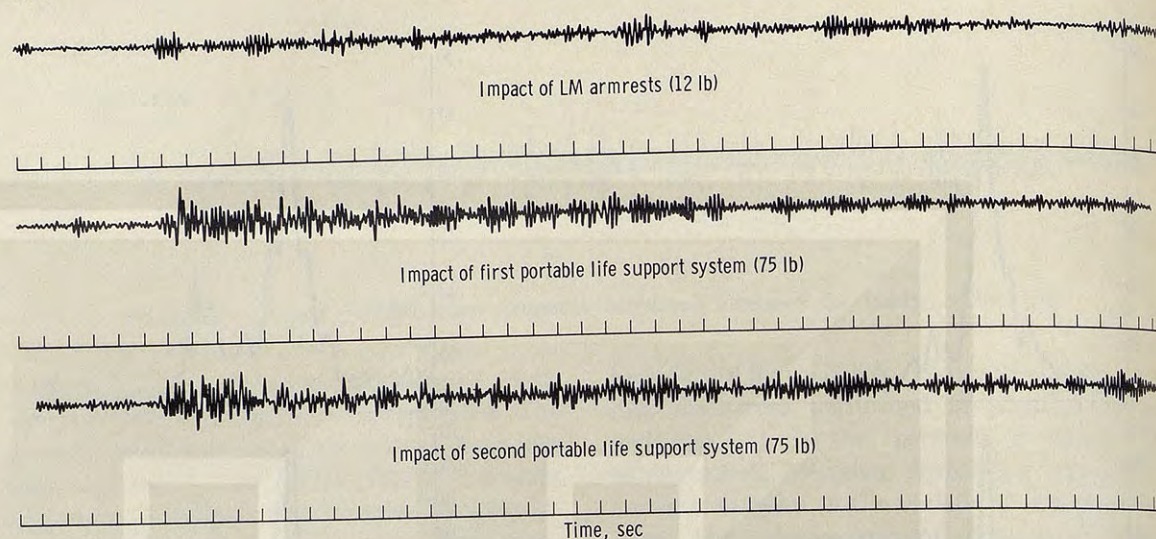


FIGURE 6-9. — Seismic signals recorded by the SP seismometer when various objects ejected from the LM struck the lunar surface.

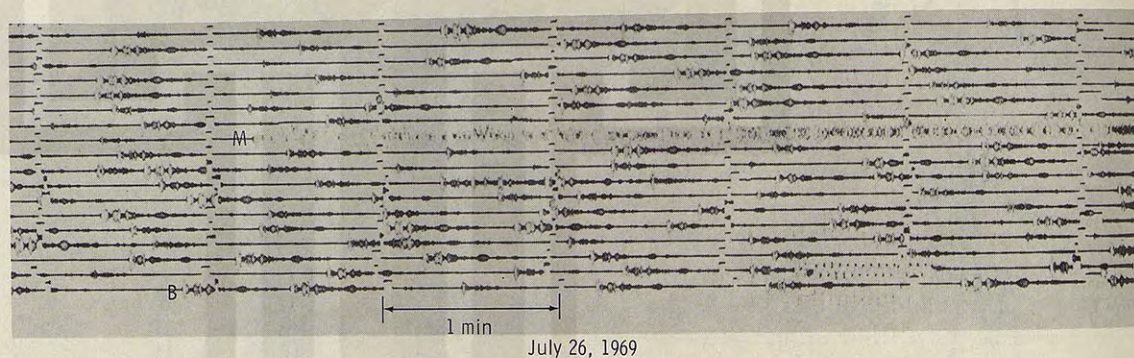


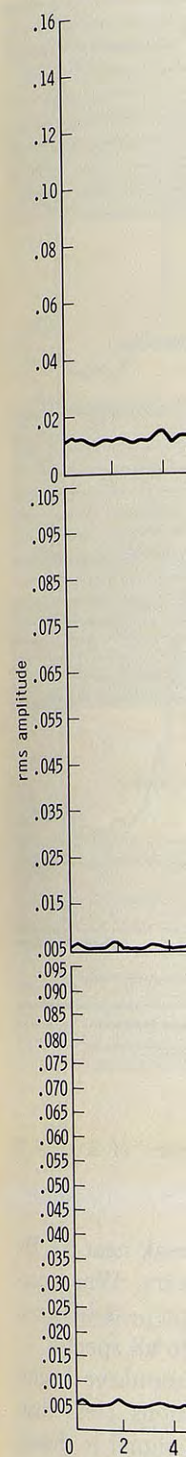
FIGURE 6-10. — Real-time record section from the SP seismometer showing type B and type M signals.

August 22, 1969) that the experiment was operational.

Spectra of three type B signals (and three type M signals) are shown in figure 6-11. The dominant spectral peak is 8.0 Hz. A subordinate peak at 6.5 Hz is also suggested. These type B events occurred after LM ascent. Before ascent, the predominant frequency was approximately 7.2 Hz. As mentioned previously, this shift in resonant frequency can be explained as the result of removing the mass of the ascent stage from the LM. The repetitive character of type B events, the apparent correlation of type B signals with LM resonant frequencies, and the eventual

disappearance of type B signals have led to the tentative conclusion that the signals were produced within the LM structure, presumably by venting or circulating gases or liquids, or both.

Type M. In the 34-hr interval between 23:00 hr on July 25, 1969, and 09:00 hr on July 27, 1969, 14 seismic signals with unusually large amplitudes and long duration were recorded. These signals began impulsively and lasted up to 7 min for the largest trains. Low frequencies (one-tenth to one-fifteenth Hz) associated with the largest of these wave trains were also observed on the LP vertical-component seismometer (LPZ) records. No related signal was



FIGURE

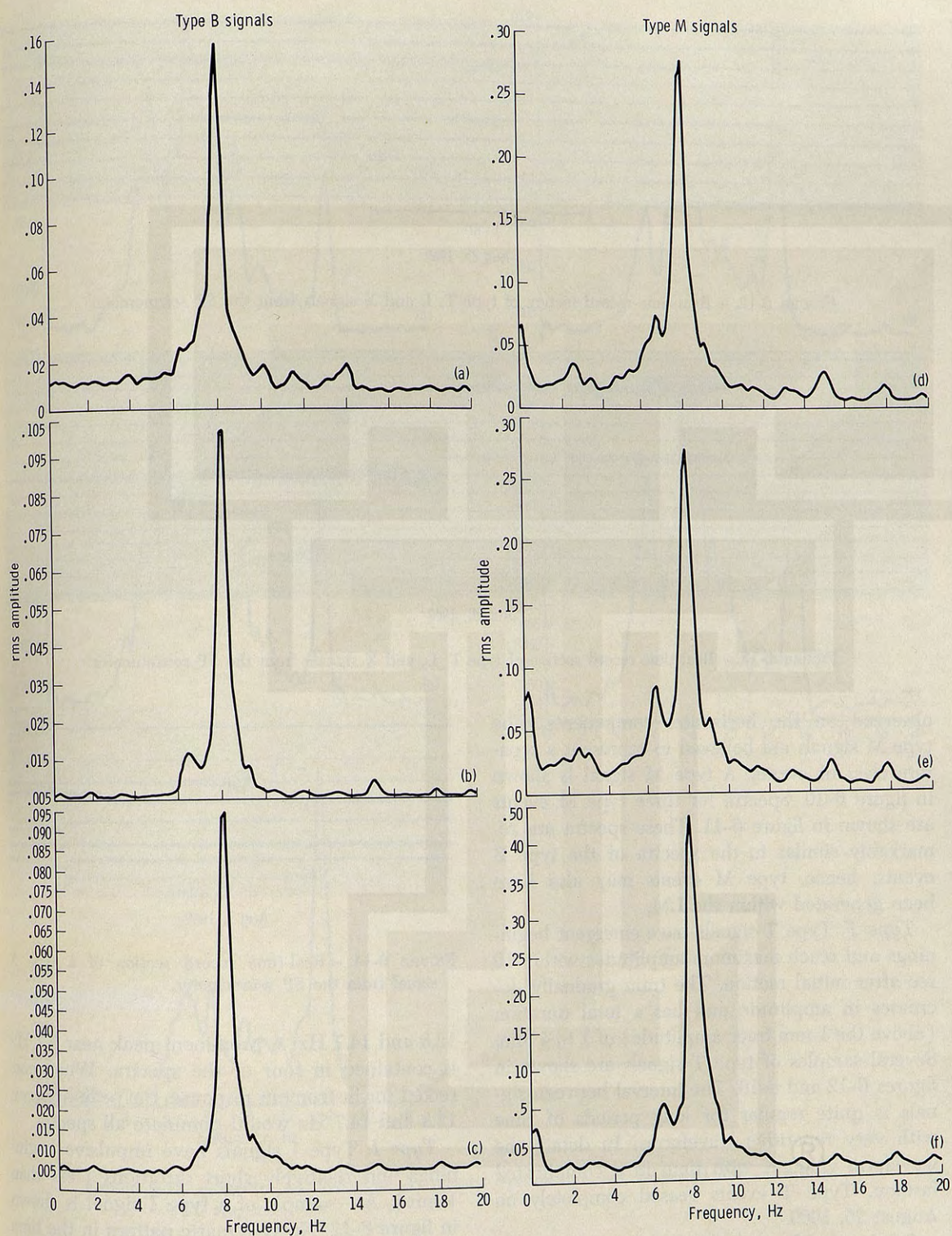


FIGURE 6-11.— Spectra of type B signals (samples (a), (b), and (c)) and type M signals (samples (d), (e), and (f)). Spectra are not corrected for instrument response.

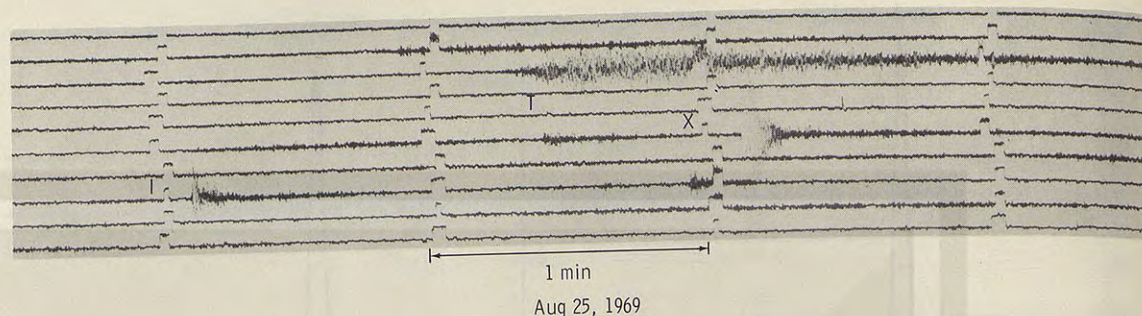


FIGURE 6-12. — Real-time record section of type T, I, and X signals from the SP seismometer.

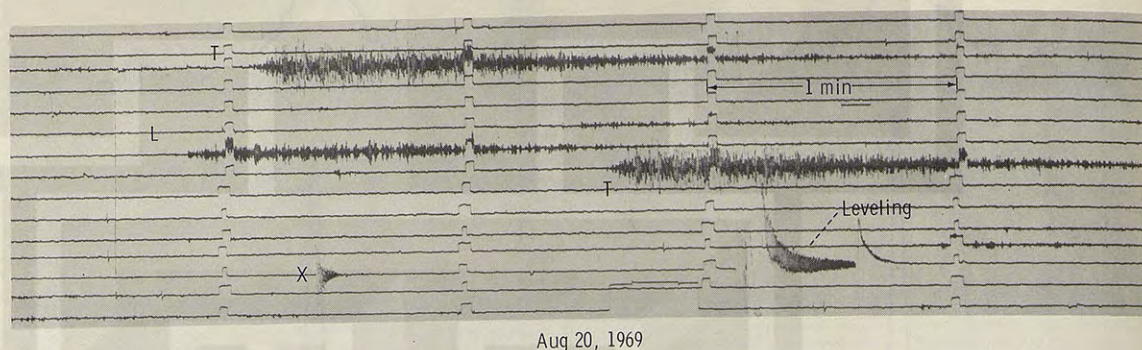


FIGURE 6-13. — Real-time record section of type T, L, and X signals from the SP seismometer.

observed on the horizontal components. The type M signals are believed to represent a separate class of events. A type M signal is shown in figure 6-10. Spectra for three type M events are shown in figure 6-11. These spectra are remarkably similar to the spectra of the type B events; hence, type M events may also have been generated within the LM.

Type T. Type T signals have emergent beginnings and reach maximum amplitudes within 10 sec after initial motion. The train gradually decreases in amplitude and has a total duration (above the 1-mm trace amplitude) of 1 to 4 min. Several samples of type T signals are shown in figures 6-12 and 6-13. The interval between signals is quite regular for long periods of time with very repetitive waveforms. In detail, the waveform changes with time in a complicated fashion. Type T events ceased completely on August 25, 1969.

Spectra for five type T signals are shown in figure 6-15. All type T event spectra show a broad peak near 8 Hz and a sharp peak between

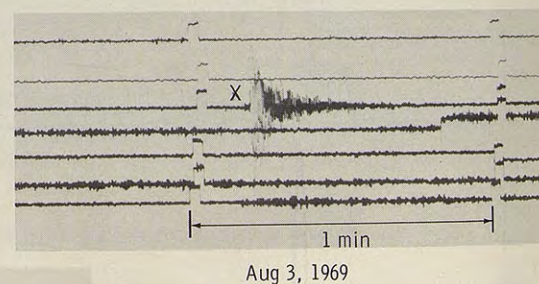
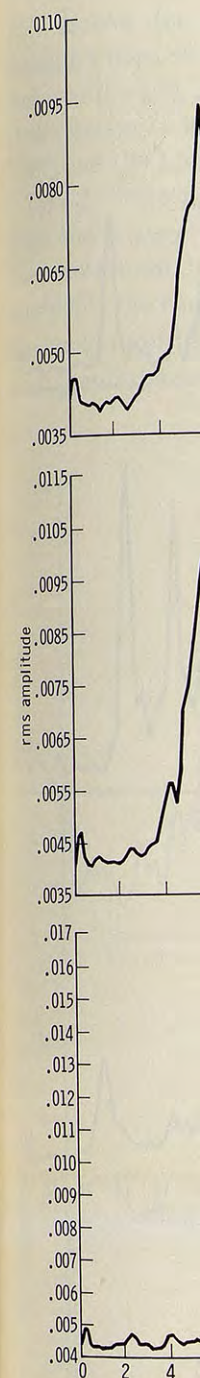


FIGURE 6-14. — Real-time record section of a type X signal from the SP seismometer.

12.8 and 14.7 Hz. A prominent peak near 5.7 Hz is contained in four of the spectra. When corrected for instrument response, the peak between 12.8 and 14.7 Hz would dominate all spectra.

Type I. Type I signals have impulsive beginnings and relatively short durations (less than 1 min). An example of a type I signal is shown in figure 6-12. No systematic pattern in the time of occurrence has been found for this type of signal. Spectra of seven type I signals are shown in figure 6-16. Samples (a), (b), and (c) in



FIGURE

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Samples (d), (e)

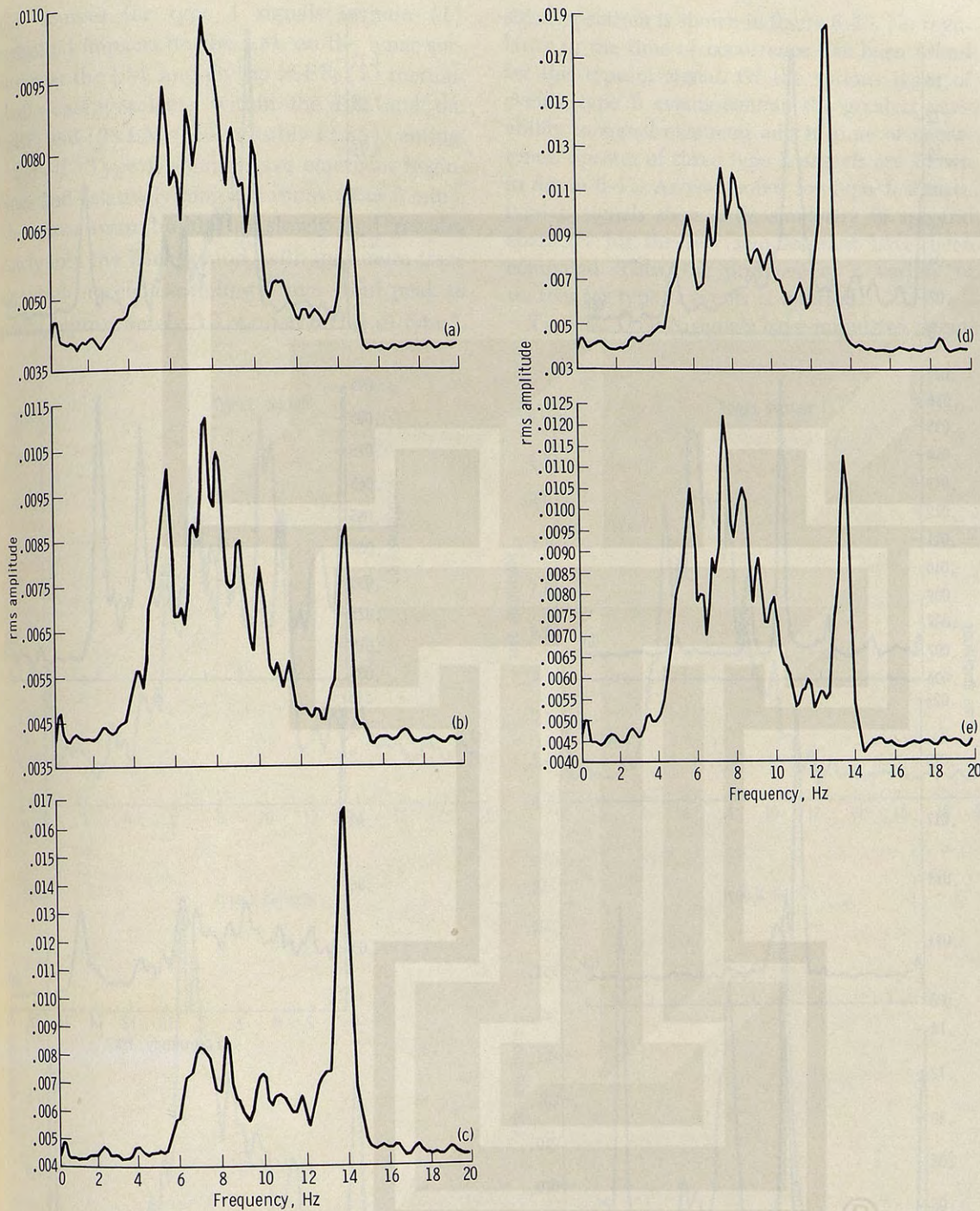


FIGURE 6-15.— Spectra of five type T signals. Spectra are not corrected for instrument response.

figure 6-16 are similar; all have a sharp peak near 8 Hz and a subordinate peak near 15 Hz. Samples (d), (e), and (f) in figure 6-16 are

distinctly different from one another and from the first group. It is evident that several source mechanisms are involved in type I signals. Pos-

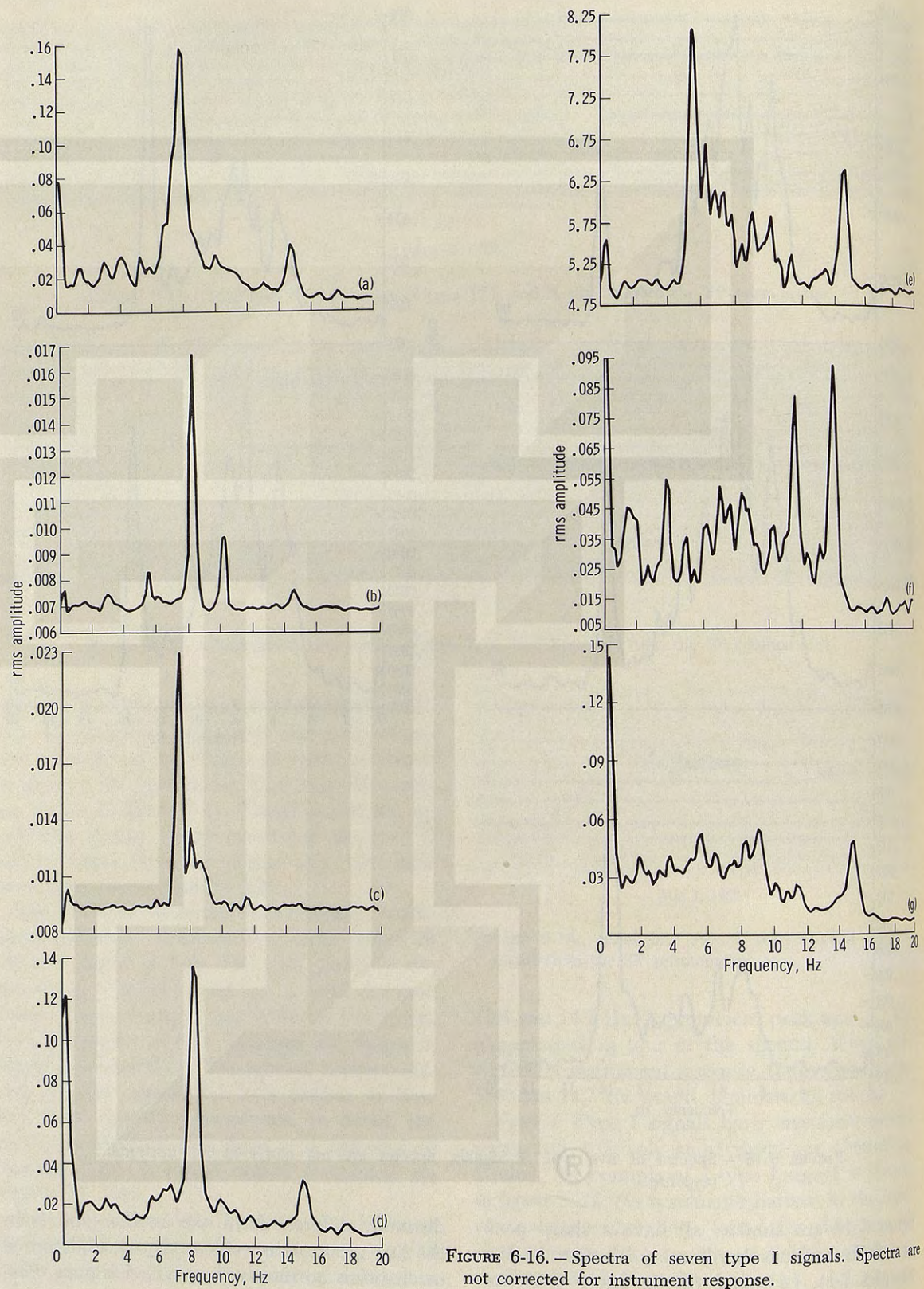


FIGURE 6-16.—Spectra of seven type I signals. Spectra are not corrected for instrument response.

sible sources for meteoroid impact face near the LM. elastic energy re PSEP; and (3) LM Type L. Type L rings and relative The wave train slowly into the ba amplitude rarely peak (approximat

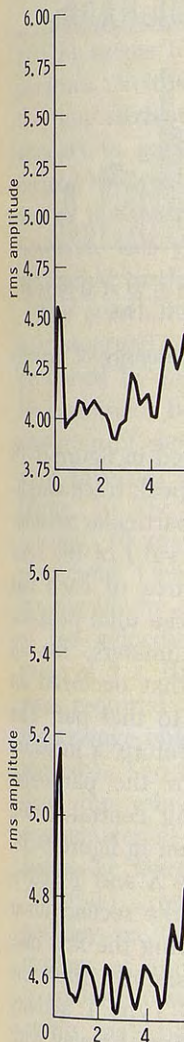


FIGURE 6-17.—Spectra of seven type I signals. Spectra are not corrected for instrument response.

sible sources for type I signals include (1) meteoroid impacts on the LM, on the lunar surface near the LM, and on the PSEP; (2) thermoelastic energy release within the LM and the PSEP; and (3) LM (and possibly PLSS) venting.

Type L. Type L signals have emergent beginnings and relatively long durations (1 to 6 min). The wave train builds up slowly and recedes slowly into the background, with maximum trace amplitude rarely exceeding 5 mm from peak to peak (approximately $3.3 \text{ m}\mu\text{m}$ at 8 Hz). A type L

signal spectrum is shown in figure 6-13. No regularity in the time of occurrence has been found for this type of signal. Of the various types of events, type L events contain the greatest variability in signal character and in time of occurrence. Spectra of three type L signals are shown in figure 6-17. As was noted for type I signals, type L signals show little similarity in spectral character for the few samples that have been computed. Thus, the presence of a variety of sources for type L events is inferred.

Type X. Type X signals have impulsive begin-

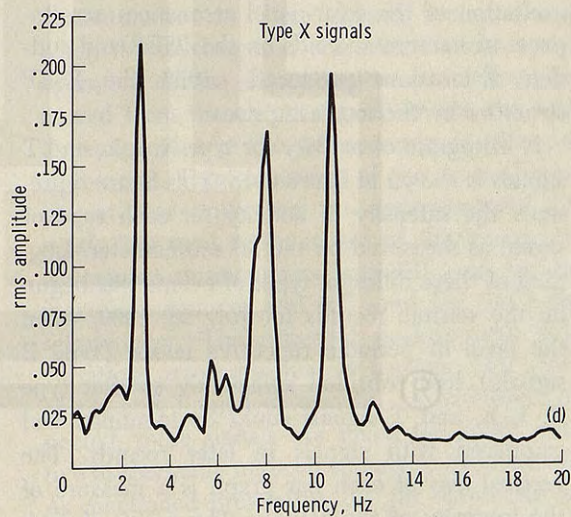
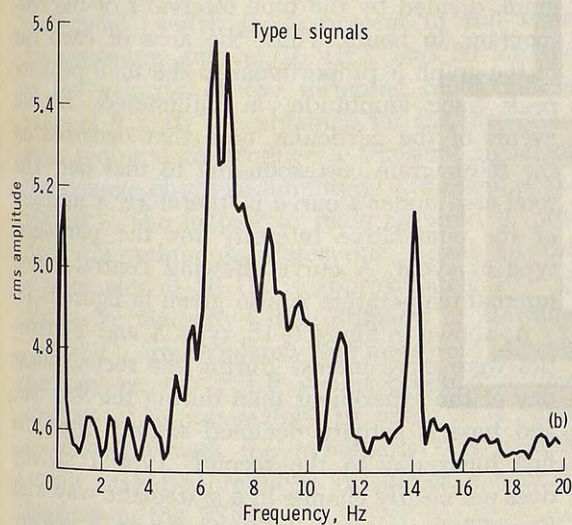
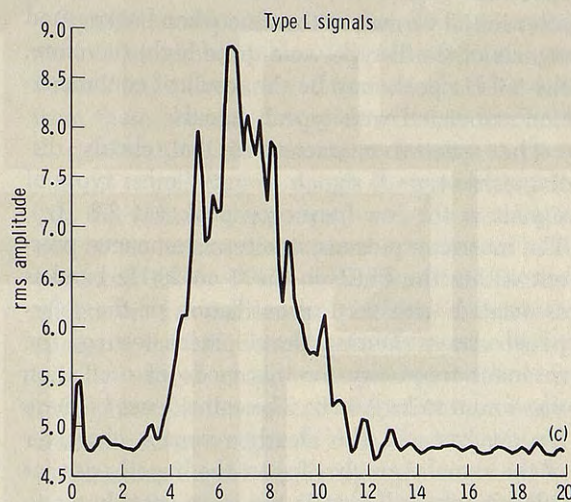
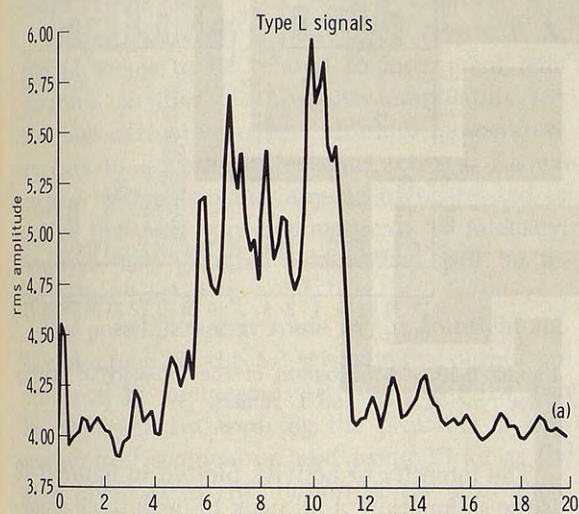
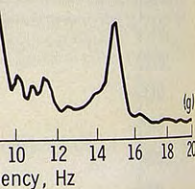
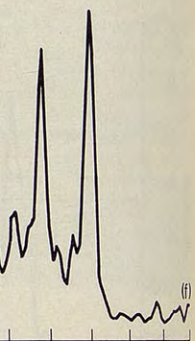
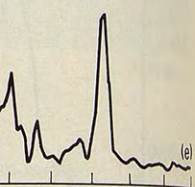


FIGURE 6-17. — Spectra of type L signals (samples (a), (b), (c)) and type X (sample (d)) signals. Spectra are not corrected for instrument response.

nings and relatively short durations (normally less than 10 sec). Maximum amplitudes occur at the beginning of the wave train and decay exponentially with a low-frequency (2 to 3 Hz) component that is usually evident in the tail of the train. Several examples of type X signals are shown in figures 6-12, 6-13, and 6-14. No regularity in the time interval between type X events has been found. The spectrum of a type X signal is shown in figure 6-17. Prominent peaks occur at 2.8, 8.0, and 10.8 Hz. When corrected for instrument response, the peaks at 2.8 Hz and at 10.8 Hz are dominant. The signal for which the spectrum (fig. 6-17) is shown occurred 38 hr after initial turnon, at the time when background signals of the B type were quite high; therefore, the 8.0-Hz peak may be the result of contamination associated with type B signals.

The spectral characteristic that clearly distinguishes type X signals from the other types of signals is the low-frequency peak (at 2.8 Hz). The most conspicuous structural resonance present within the PSEP in the 0- to 20-Hz band is associated with vertical oscillation of the solar-panel arrays. During development testing, the resonant frequency for this mode of oscillation was found to be 2.6 Hz. The coincidence of these frequencies and the clearly resonant character of the signal strongly support the hypothesis that solar-panel oscillation is the main contributor to type X signals. The most obvious sources for excitation of the solar-panel resonances are impacts of micrometeoroids on the PSEP and sudden dislocations produced within the PSEP structure by thermoelastic stress.

A histogram of activity for type X, I, L, and T signals is shown in figure 6-18. This figure represents the intensity of activity for each type of signal as measured on the SP seismometer. Logging of these different types of events was begun on the seismic records for July 28, 1969, when the level of periodic repetitive noises (type B signals) had subsided sufficiently so that type X, I, L, and T signals could be identified and compared with signals in later records. The vertical axis of each bar graph is a measure of the intensity of the activity. The width of each bar of the graph spans the time interval on each seismogram (usually 12 hr).

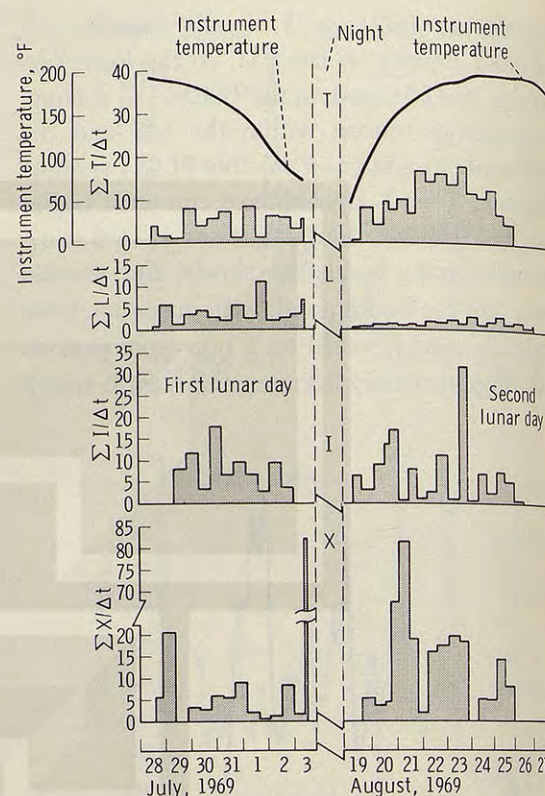


FIGURE 6-18. — A histogram of the intensity of activity for type X, I, T, and L signals.

The intensity of activity plotted in figure 6-18 is the summation of all peak-to-peak trace amplitudes greater than 1 mm on a particular seismogram, divided by the time interval t of the seismogram, in hours. Thus, the area of each bar of the graph is proportional to the total peak-to-peak trace amplitude, in millimeters, for all events of the particular type that occurred on the seismogram corresponding to that bar. The total area under a curve is, therefore, a measure of the cumulative intensity for the particular type of event. A curve showing central-station internal temperature is also given in figure 6-18.

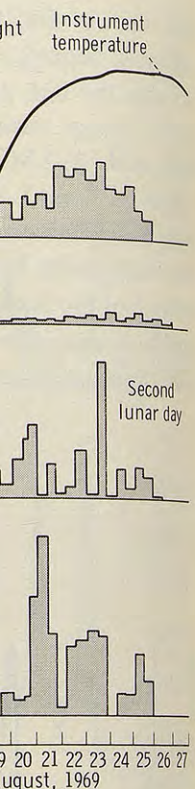
As shown in figure 6-18, type X and T activities were more intense during the second lunar day of the experiment than during the first one, and type L activity declined slightly from the first lunar day to the second. Type I activity does not clearly change in a systematic way with time. There is a possibility that type X activity varies periodically, with the maxima of intensity that occurred at 2- to 3-day intervals during both

the first and second lunar days. The first lunar day was operational. peaks of type X activity occurred during the second lunar day. In figure 6-18, type X activity is especially prominent during the second lunar day. It increased in intensity and appeared in the afternoon at Tranquility. It appears to have occurred about 24 hr before the end of the first lunar day. Type X and I activity ended at this time.

None of these activities (type X, I, and T) seems to be related to temperature. Neither the time derivative of the activity nor the activity itself appears to govern meteor streams or any of the most prominent events; however, this possibility is being investigated further.

The possibility of activity being produced by meteor impacts on the lunar surface is being examined. Based on observation of meteor impacts, the mass involved in the impact, 10 Hz frequency, 10 m/sec velocity, and the displacement (which is proportional to the maximum g-force as the velocity value of 2×10^4 m/sec mass required to produce the average observed peak-to-peak). The reduction of the minimum seismic activity at the seismometer at the Apollo 11 site. Using the meteor impact data (ref. 6-1), approximately one impact per day on the lunar surface. The motions of the Apollo 11 lander are consistent with the events may be produced by impacts on the lunar surface.

At this point, the possible sources of seismic signals are being investigated.



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the first and second lunar days the experiment was operational. A tendency exists for successive peaks of type X activity to decline during each lunar day. In figure 6-18, the highest peak of type X activity is reached soon after the beginning of the second lunar day. Type T activity is especially prominent during this second lunar day. It increased to a maximum and then disappeared in the interval between sunrise and local noon at Tranquility Base. Type T activity appears to have ended completely approximately 24 hr before the end of the recording period. Type X and I activities also appear to have ended at this time.

None of these types of activity (types T, X, and I) seems to be related to instrument temperature. Neither the absolute temperature nor the time derivative of the absolute temperature appears to govern the seismic activity. Known meteor streams do not appear to be related to any of the most conspicuous peaks of intensity; however, this possible relationship will be investigated further.

The possibility that some of the transient signals observed on the SP seismometer output are produced by meteoroids striking the PSEP can be examined. By applying the principle of conservation of momentum and using 10 kg as the mass involved in the motion of the instrument frame, 10 Hz as a representative signal frequency, 10 $m\mu m$ as the maximum frame displacement (which is 20 percent of full scale for maximum gain at 10 Hz), and 30 km/sec as the velocity of the incoming meteoroid, a value of 2×10^{-7} is obtained for the meteoroid mass required to produce a transient signal of the average observed amplitude (10 $m\mu m$, peak-to-peak). The meteoroid mass required to produce the minimum detectable signal on the seismometer at 10 Hz is approximately 10^{-9} g. Using the meteoroid flux estimates of Hawkins (ref. 6-1), approximately five meteoroid impacts per day on the PSEP would produce seismic motions of approximately 10 $m\mu m$. This value is consistent with the hypothesis that type X events may be produced by direct meteoroid impacts on the PSEP.

At this point in the investigation, the following possible source mechanisms for the observed seismic signals are suggested:

- (1) Venting gases from the LM and PLSS's and circulating fluids within the LM
- (2) Thermoelastic stress relief within the LM and PSEP structures
- (3) Meteoroid impacts on the LM, the PSEP, and the lunar surface
- (4) Displacement of rock material along steep lunar slopes
- (5) Moonquakes
- (6) Instrumental effects

Feedback (Tidal) Outputs and Instrument Temperature

Signals corresponding to the slowly varying motion of each of the LP seismometers are transmitted on separate data channels. The data from these channels are referred to as feedback or tidal outputs. Instrument sensitivity at these outputs is sufficient to detect changes in gravity (on the vertical component) and the associated tilts of the lunar surface (on the horizontal components). In the PSEP, however, direct thermal effects on the instrument platform and on the spring of the LPZ seismometer were expected to greatly exceed changes associated with lunar tides. Internal instrument temperature was also transmitted as a separate data channel.

Variations in the feedback signals and instrument temperature are plotted in figure 6-19 for the total 21-day recording period. Step-function discontinuities in these signals are produced when the leveling and centering motors are in operation. These discontinuities have been removed from the output signal; hence, the total dynamic range of the seismometers is exceeded in the plot. Total excursion of the vertical component was equivalent to approximately 142 mgal. The total range in tilt of the horizontal-component seismometers was 370 μrad for the y -axis seismometer and 825 μrad for the x -axis seismometer. The expected peak-to-peak tidal variations are approximately 1 arcsec (4.9 μrad) of tilt and 1 mgal of gravity. As had been expected, these signals are much too small, relative to thermally induced signals, to be observed. As mentioned previously, the tilt variations are produced by a combination of actual tilting of the instrument platform in the lunar surface material, tilting associated with thermal distor-

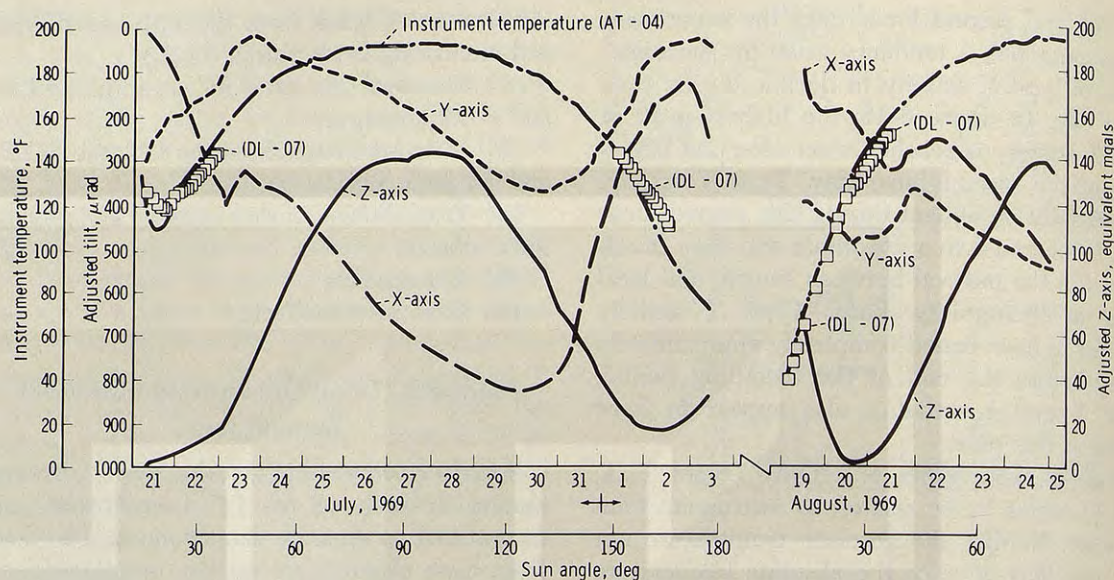


FIGURE 6-19.—Variations in feedback signals and instrument temperature over the 21-day recording period.

tions of the instrument platform, and direct thermal effects on the elements of the seismometers and on the seismometer leveling systems. Long-term variations in the LPZ seismometer feedback signal are produced primarily by direct thermal effects on the suspension spring.

Scientific Results

Perhaps the most important result of the PSEP is the demonstration that it is possible to explore another planet with the powerful tools of seismology. Despite the difficulty of interpreting the data in the presence of the background noises that resulted from the proximity of the experiment to the LM, sufficient information has been accumulated to show that greatly improved data can be obtained from the first Apollo Lunar Surface Experiments Package (ALSEP) by making simple changes in the operating procedure. Specific improvements in operating procedure that should be made include the following:

- (1) The seismometer package must be moved farther from the LM to reduce interfering noise level caused by the LM.
- (2) The sensor must be removed from the central station.

- (3) Better thermal control must be achieved.
- (4) Higher sensitivity must be sought.

All these improvements, except item (4), were planned for the Apollo 12 mission. Higher sensitivity of the seismic instruments must await the design changes that the advanced ALSEP will make possible.

Another important result of the PSEP is the discovery that the background noise level on the Moon is extremely low. Before these data were obtained, the level of lunar background noise was uncertain by several orders of magnitude. According to one popular hypothesis, the large diurnal thermal variations within the lunar surface material produced stresses that would lead to spallation and fracture and, consequently, to a high level of background noise. Another hypothesis proposed that meteoroid impacts were sufficiently numerous to create a significant continuous noise level. Still another hypothesis cited the absence of an atmosphere, oceans, and cultural activities to support the contention that the background noise level on the Moon should be much lower than the level on the Earth. The PSEP indicated that the background seismic-noise levels on the Moon are extremely low, as described in the following sections.

SP Backg

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SP Background Seismic-Signal Level

A histogram of background seismic-signal level which was recorded by the SP seismometer for the first 9 lunar days of the experiment is shown in figure 6-20. The high-amplitude signal that occurs immediately after turnon is produced partly by astronaut activities and partly by signals that are tentatively attributed to the LM. These levels decreased steadily over a period of 8 days. After 8 days, occasional activity, as discussed in the section entitled "Description of Recorded Seismic Signal," was observed. Thus, the continuous background seismic signal near 1 Hz is less than $0.3 \text{ m}\mu\text{m}$, which corresponds to system noise. Maximum signal levels of $1.2 \text{ }\mu\text{m}$ at frequencies of 7 to 8 Hz were observed during the period when the astronauts were on the surface.

LP Vertical-Component Seismometer

Except for the occasional occurrence of transient signals of instrumental origin, the background seismic-signal level on the LPZ seismometer is below system noise, that is, below $0.3 \text{ m}\mu\text{m}$ over the period range from 1 to 10 sec. This level is between 100 and 10 000 times less than average background levels observed on Earth in the normal period range for microseisms (6 to 8 sec).

LP Horizontal-Component Seismometers

Continuous seismic background signals of extremely small amplitudes (10 to $30 \text{ m}\mu\text{m}$, peak-to-peak) were observed on the records from the two LP horizontal-component seismometers. The amplitude of these signals decreased considerably for a 2- to 3-day interval near lunar noon, when the rate of change of external temperature with time is at a minimum. The signals are very low frequency with periods of from 20 sec to 2 min. It is assumed that these signals correspond to the tilting of the instruments caused by a combination of thermal distortions of the metal pallet, which serves as the base of the seismometer, and a rocking motion of the pallet in the lunar surface material. The rocking motion could also be produced by thermal effects. However, the horizontal component of true lunar seismic-signal background level at shorter peri-

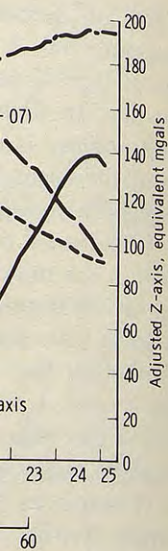
ods (less than 10 sec) also appears to be less than $0.3 \text{ m}\mu\text{m}$. The character of the background signals on the LP seismometers is shown in figure 6-5.

Of the many signals that have been recorded, at least some were produced by the LM. Many signals may be of natural origin; that is, they may have been generated by moonquakes, impacts, or movement of surface rocks. However, none of the observed signals has the pattern normally observed in recordings of seismic activity on Earth (with the possible exception of signals produced by local volcanic events and by landslides). Distinct phases corresponding to the various types of waves are not apparent in any of the recorded seismic signals, and most wave trains are of long duration. The high sensitivity at which the PSEP instruments were operated would have resulted in detection of many distinctive seismic events if the Moon were as seismically active as the Earth and if lunar rocks transmitted seismic waves as effectively as do Earth rocks. The fact that a large number of unmistakable seismic events were not observed during 21 days of operation is a major scientific result. To describe this observation, it is convenient to introduce the term "seismic receptivity."

Seismic receptivity is a measure of the overall effectiveness with which seismic waves are generated, transmitted, and detected at any given point for any given body. The seismic receptivity is the product of involving (1) the seismicity of the body, that is, the rate of seismic energy release, (2) the transmissibility of the medium through which the waves propagate, and (3) the level of background seismic noise at the sensor location.

The background seismic noise of the Moon (for the sensor at Tranquility Base) is low. This low background level results in high seismic receptivity for the sensor. The problem to be attacked by analysis of the data already obtained and data expected from future missions is to determine the extent to which each of two factors, seismicity and transmissibility, is responsible for the small number of distinctive seismic events that have been recorded.

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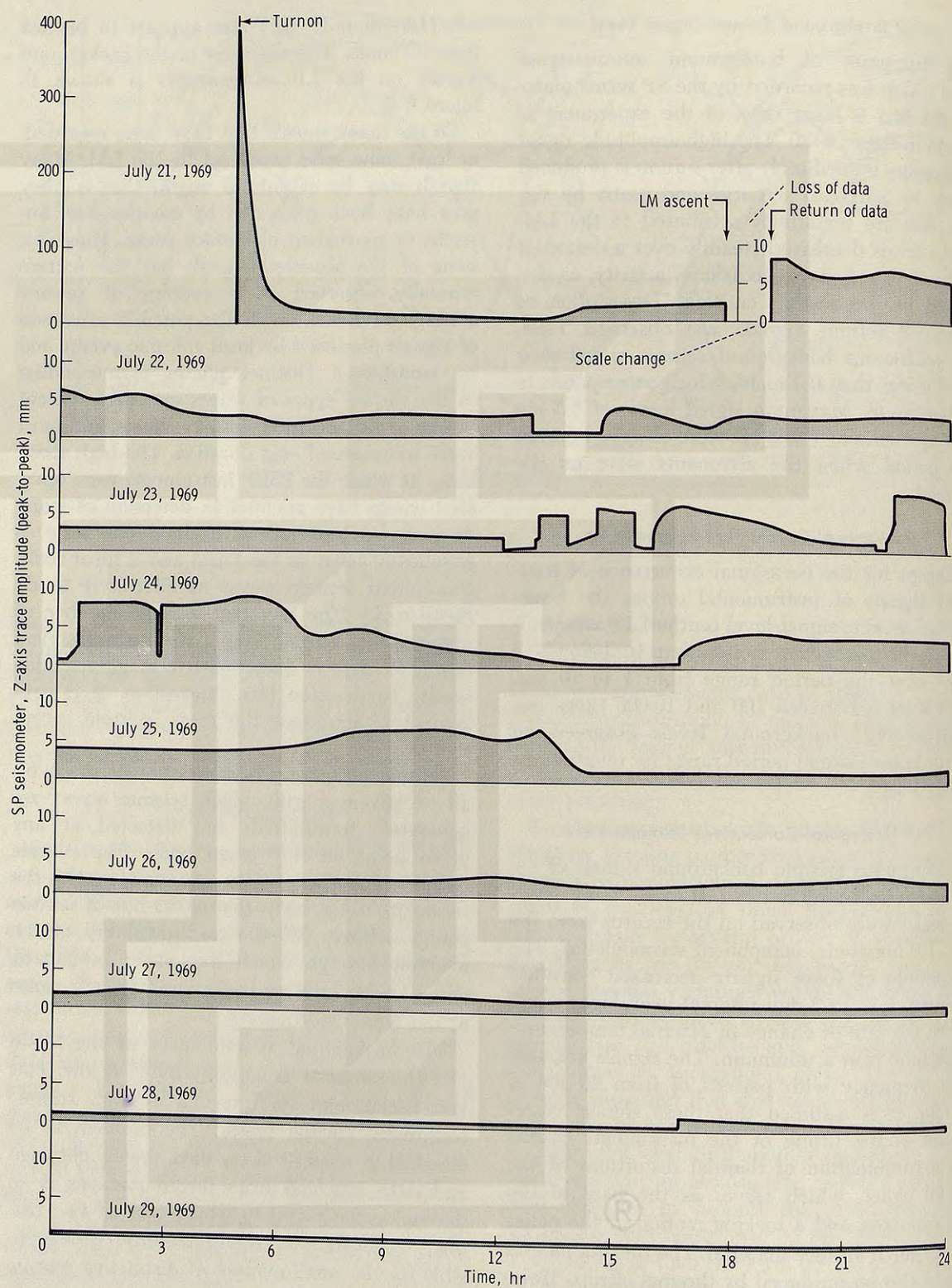


FIGURE 6-20. — Histogram of signal level from the SP seismometer. A 1-mm trace amplitude equals $1.9 \text{ m}\mu\text{m}$ for the predominant signal component (8 Hz).

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mic receptivity are the heterogeneity of lunar material, which would scatter the seismic waves; a low- Q (where Q is the transmissibility quality factor) interior, which would absorb seismic waves; and an inability of the lunar material to store high stress. Low seismicity, if confirmed by future missions, would imply the absence of tectonic processes within the Moon such as those associated with major crustal movements on Earth.

One hypothesis that could explain the observations is that the body of the Moon is very heterogeneous, at least in its outer regions. The near-surface material is certainly heterogeneous in character, as evidenced by the great numbers of visible craters and surface fractures. This heterogeneity may extend deep into the body of the Moon. The scattering of seismic waves that would occur in propagation through a highly heterogeneous material would tend to increase the duration of the observed seismic wave and to suppress the appearance of distinct phases within the wave train. The PSEP station was in one of the mare regions, which are thought to be great lakes of solidified lava. If this hypothesis is true, the maria would be expected to be among the most homogeneous regions of the Moon. However, since the original formation of the maria, meteoroid impacts may have converted these structures to rubble. If the age of Mare Tranquillitatis is as great as first results indicate (discussed in chapter 5), the process of fracturing by impact may have proceeded to a very great extent. Much of the visible evidence for such fracturing may be hidden by the overlying blanket of fragmental material. However, it should be noted that nothing in the present observations precludes the possibility of a high-temperature (low- Q) lunar interior. This would also contribute to low seismic receptivity.

With one lunar seismic station, one should not expect to do effective seismology on the Moon, unless the Moon were similar to the Earth, with an abundance of natural seismic sources, and unless the signals were similar in character to those observed on Earth, so that one could draw by analogy on Earth experience. Neither of these two criteria appears to have been met. Seismic experiments, nevertheless, will lead eventually

to answers to questions concerning the structure and dynamics of the Moon. Results will come more slowly than had been hoped, and there will be greater dependence upon the establishment of a network of stations and use of artificial sources.

Meteoroid impacts are a major factor in shaping the lunar surface. Determination of the size and frequency distribution of meteoroid impacts is necessary to estimate quantitatively the rates of crater formation and erosion. A store of information, begun with the PSEP data, will be uniquely suited to the study of this problem.

Two important implications that will affect future seismic experiments emerge from the preliminary analysis of the PSEP data. The effectiveness of the use of moonquakes for investigation of deep lunar structure is low, despite the high sensitivity of the seismometers used. However, the low background noise observed demonstrates that greater sensitivity can be used. The effectiveness of the present instrumentation will be greatly enhanced when a planned network of three ALSEP stations is operable. Even if the seismicity of the Moon is considerably less than that of the Earth, this network can reasonably be expected to record several significant lunar seismic events. Data from even a single well-recorded lunar seismic event could be sufficient to determine major structural features of the Moon. Also, even if the Moon has an extremely low seismicity, probing of the deep lunar interior by use of artificial sources, such as the impacts of a Saturn IVB stage and the LM ascent stage, is a strong possibility.

The low seismic-noise level measured by the PSEP indicates that the major modification needed in the advanced ALSEP is increased sensitivity of the seismometer system. Increased sensitivity may compensate for the apparent low seismicity of the Moon to the extent that moonquakes can be as effective for investigation of deep lunar structure as earthquakes are for study of the interior of the Earth.

Reference

- 6-1. HAWKINS, GERALD S.: The Meteor Population, Research Report No. 3. NASA CR-51365, August 1963.

7. Laser Ranging Retroreflector

C. O. Alley, P. L. Bender, R. F. Chang, D. G. Currie, R. H. Dicke, J. E. Faller, W. M. Kaula, G. J. F. MacDonald, J. D. Mulholland, H. H. Plotkin, S. K. Poultney, D. T. Wilkinson, Irvin Winer, Walter Carrion, Tom Johnson, Paul Spadin, Lloyd Robinson, E. Joseph Wampler, Donald Wieber, E. Silverberg, C. Steggerda, J. Mulendore, J. Rayner, W. Williams, Brian Warner, Harvey Richardson, and B. Bopp

Concept of the Experiment

The compact array of high-precision optical retroreflectors (cube corners) deployed on the Moon 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 prevent a laser beam from being smaller than approximately 1 mile in diameter at the Moon. The curvature of the lunar surface results in one side of the short pulse being reflected before the other side, producing a reflected pulse measured in microseconds, even if the incident pulse is measured in nanoseconds. The retroreflector 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 retroreflective 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.

With the ± 15 -cm uncertainty, monitoring the changes in point-to-point distances from Earth to the lunar reflector (by daily observations for many years) will produce new information on the dynamics of the Earth-Moon system. 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). Some of these objectives are discussed in references 7-1 to 7-4. Estimates made by P. L. Bender of improvements expected in some of these categories are shown in tables 7-I to 7-III.

Properties of the Laser Ranging Retroreflector

Although the Laser Ranging Retroreflector (LRRR) is simple in concept, the detailed design of a device that would satisfy the stated scientific aims has received much attention. The primary design problem has been to avoid systematic gaps in ranging data expected to result from the extreme variation in thermal conditions on the Moon (from full Sun illumination to lunar night). A preliminary design based on discussions among various members of the investigator group and optical engineers was put

TABLE 7-I. *Lunar orbital data parameters*

Quantity	Present accuracy (approximate)	1.5-m range uncertainty		0.15-m range uncertainty ^a	
		Accuracy	Time, yr	Accuracy	Time, yr
Mean distance	500 m	250 m	1	75 m	0.5
Eccentricity	1×10^{-7}	4×10^{-8}	1	25 m	1
Angular position of Moon with respect to perigee	2×10^{-6}	4×10^{-7}	1	1.5×10^{-8}	.5
Angular position of Moon with respect to Sun	5×10^{-7}	4×10^{-7}	1	4×10^{-9}	1
Time necessary to check predictions of Brans-Dicke scalar-tensor gravitational theory, yr	—	25	25	1.5×10^{-7}	.5
				4×10^{-8}	1
		25	25	8	8

^aThree observing stations are assumed for periods longer than 0.5 yr.

TABLE 7-II. *Lunar libration and relation of Laser Ranging Retroreflector (LRRR) to center of mass*

Quantity	Present accuracy (approximate)	1.5-m range uncertainty		0.15-m range uncertainty ^a	
		Accuracy	Time, yr	Accuracy	Time, yr
Libration parameters:					
$\beta = (C-A)/B$	1×10^{-5}	3×10^{-7}	4	3×10^{-7}	0.5
$\gamma = (B-A)/C$	5×10^{-5}	2×10^{-6}	1.5	3×10^{-8}	4
Coordinates of LRRR with respect to center of mass:				1.5×10^{-6}	.5
X_1	500 m	250 m	1	2×10^{-7}	1.5
X_2	200 m	70 m	1	75 m	.5
X_3	200 m	50 m	3	25 m	1
				40 m	.5
				7 m	1
				50 m	.5
				5 m	3

^aThree observing stations are assumed for periods longer than 0.5 yr.

TABLE 7-III. *Geophysical data determinable from LRRR*

Quantity	Present accuracy (estimated)	1.5-m range uncertainty	0.15-m range uncertainty
Rotation period of Earth, sec	5×10^{-3}	10×10^{-3}	1×10^{-3}
Distance of station from axis of rotation, m	10	3	0.3
Distance of station from equatorial plane, ^a m	20	6 to 20 ^b	0.6 to 2 ^b
Motion of the pole, ^a m	1 to 2	1.5	0.15
East-west continental drift rate observable in 5 yr, ^a cm/yr	30 to 60	30	3
Time for observing predicted 10-cm/yr drift of Hawaii toward Japan, ^a yr	15 to 30	15	1.5

^aThree or more observing stations are required.

^bDepending upon the latitude of the station.

forth by J. E. Faller in a proposal to NASA (ref. 7-5).

The first financial support provided by NASA was used to test the proposed design, which consisted of small solid-corner reflectors made of

homogeneous fused silica. The test and evaluation facilities at the NASA Goddard Space Flight Center were used to simulate the lunar environment. These tests verified that a metal coating could not be used on the reflectors and showed that the

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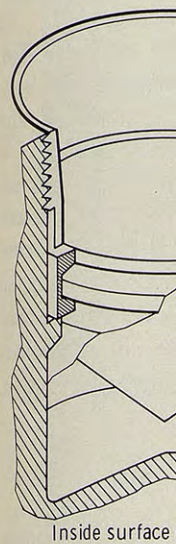
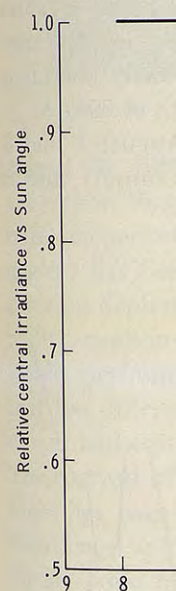


FIGURE 7-



FIGURE

failure of total internal reflection at off-axis angles posed serious problems in mounting the reflectors to maintain small temperature gradients during larger off-axis Sun angles (ref. 7-6).

The tests verified the predicted performance during lunar night and during direct Sun illumination within the total internal reflection region of angles.

The efforts of thermal and mechanical design engineers in close association with members of the investigator group solved the problems and led to the design shown in figure 7-1. The corner reflectors are lightly mounted on tapered tabs between Teflon rings, and are recessed by one-half their diameter into cylindrical cavities in a solid aluminum block. The predicted optical performance, based on thermal analyses under changing lunar conditions, is shown in figure 7-2.

The need for careful pointing of the LRRR toward the center of the Earth libration pattern is shown by figure 7-3, which displays the off-axis response of the recessed corner reflectors. (The curve is the result of averaging over azimuthal orientation and polarization dependence.) The motion of the Earth in the lunar sky because of the optical librations of the Moon is shown in figure 7-4 for the period July to October 1969.

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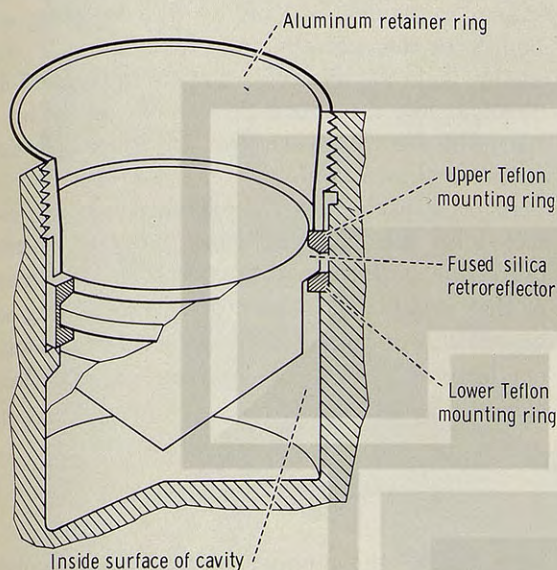


FIGURE 7-1. — Corner reflector mounting.

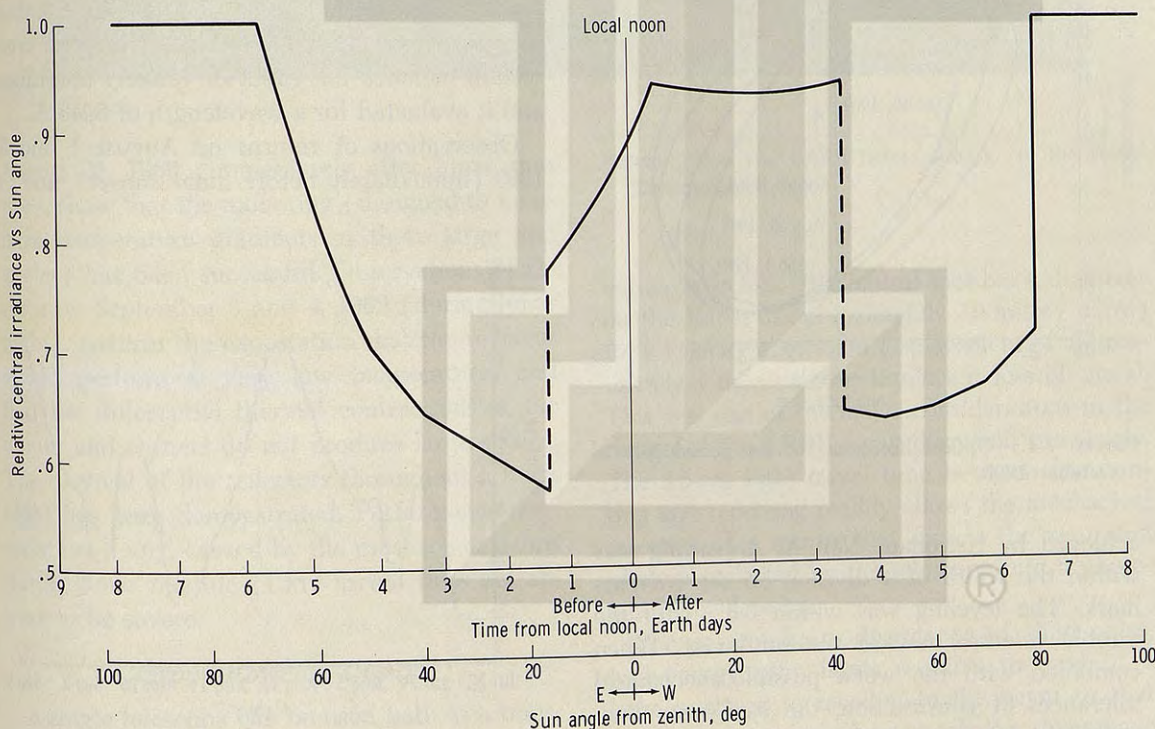


FIGURE 7-2. — Predicted optical performance as a function of Sun angle, from thermal analysis.

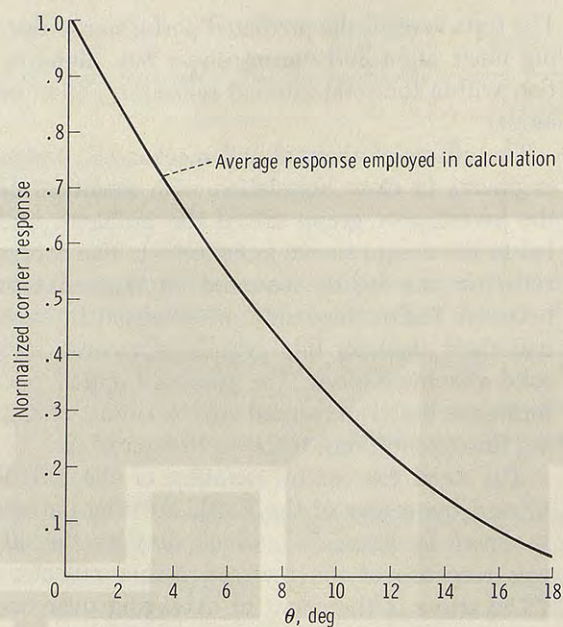


FIGURE 7-3. — Average off-axis performance of recessed circular corner reflectors.

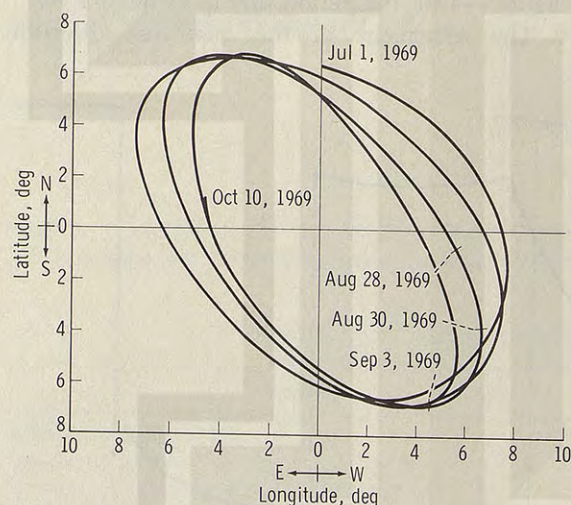


FIGURE 7-4. — Optical librations for the period July to October 1969.

achieved by Astronaut Neil A. Armstrong was within the width of a division on the compass mark. The leveling was within 0.5° , with the bubble oriented toward the southwest. When combined with the worst possible mechanical tolerances of construction, the east-west alignment is $\pm 0.7^\circ$, and the overall pointing is within 1° of the center of the libration pattern.

This excellent pointing means that the return will not fall to extremely low values during the extremes of the libration cycle. With the previous information included, the relative expected response from July 20 to September 9, 1969, is shown in figure 7-5. Figure 7-5 is an upper bound for the performance expected.

The flight hardware is shown in figure 7-6. The gnomon, the alinement marks, and the bubble level are clearly shown. In figure 7-7, the LRRR is shown deployed on the Moon.

In tests, each corner reflector which was selected for the flight array exhibited an on-axis diffraction performance greater than 90 percent of that possible for a corner reflector having no geometrical or homogeneity defects. The on-axis, nondistorted performance is conveniently characterized by a differential scattering cross section.

$$\left. \frac{d\sigma}{d\Omega} \right|_{180^\circ} = 5 \times 10^{11} \text{ cm}^2/\text{steradian}$$

which yields the number by which the photon flux density (photons per square centimeter) incident on the reflector array must be multiplied to give the number of photons per steradian intercepted by the telescope receiver. The cross section includes the effect of velocity aberration and is evaluated for a wavelength of $6943 \text{ \AA}$.

Observations of returns on August 1 and 3, 1969 (immediately before lunar sunset), and on

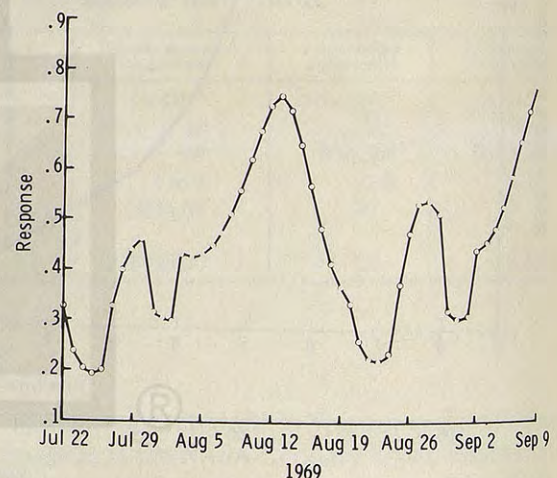


FIGURE 7-5. — Upper bound of LRRR efficiency as a function of time.

August 20, 1969 (rise), show that the temperature (angles) has been turns on September night), confirm would perform that the difference mount and corner. The survival of night has been radiation, if any, during lunar month appear to be severe.

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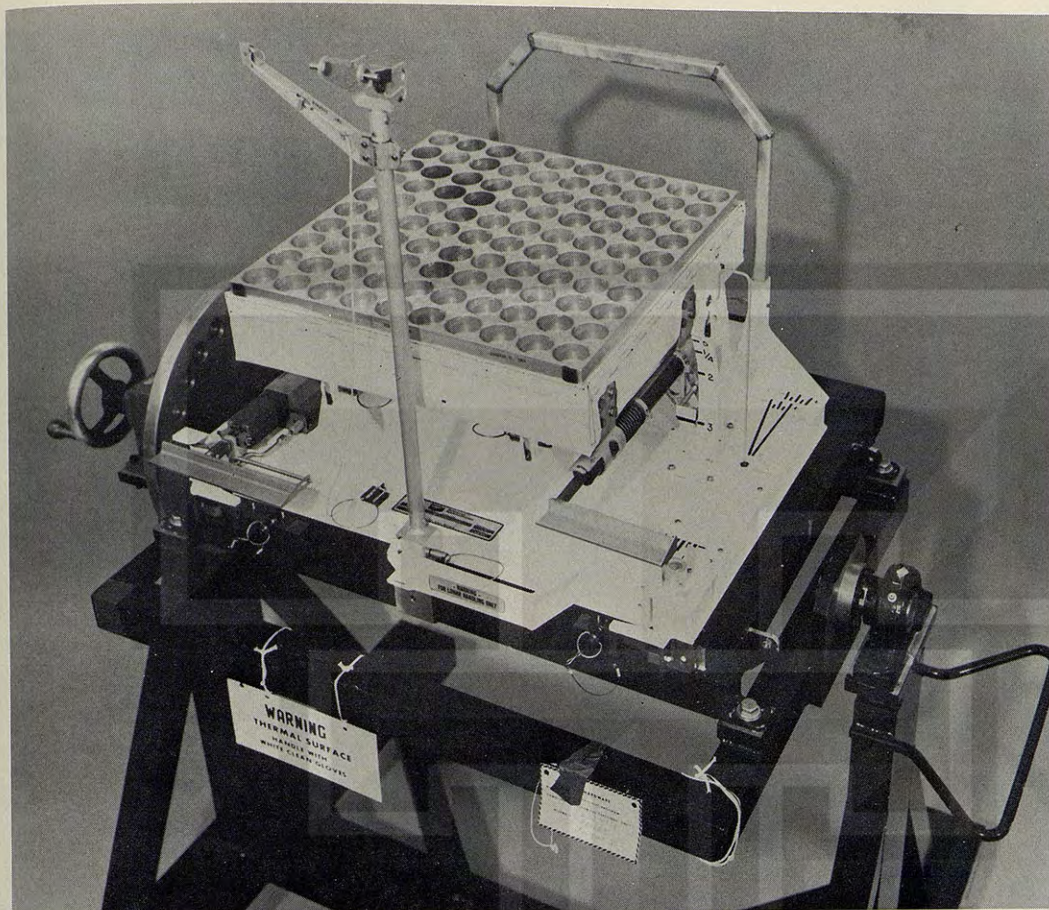


FIGURE 7-6. — The LRRR before stowage in the scientific equipment bay.

August 20, 1969 (immediately after lunar sunrise), show that the mounting (designed to minimize temperature gradients at these large Sun angles) has been successful. Observations of returns on September 3 and 4, 1969 (during lunar night), confirm the expectation that the reflector would perform at very low temperatures and that the differential thermal contractions of the mount and corners do not produce large strains. The survival of the reflectors throughout a lunar night has been demonstrated. Performance degradation, if any, caused by the presence of debris during lunar module (LM) ascent does not appear to be severe.

Ground Station Design

A single telescope can be used both 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 10 miles) allows for a velocity aberration displacement of approximately 1 mile without significant loss of signal. This was one of the major considerations in the design of the LRRR array discussed previously. The 2.5-sec light travel time between transmitting and receiving readily 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 to recollimate the beam so that the beam is narrowed to match the divergence allowed by the atmospheric fluctuations of the

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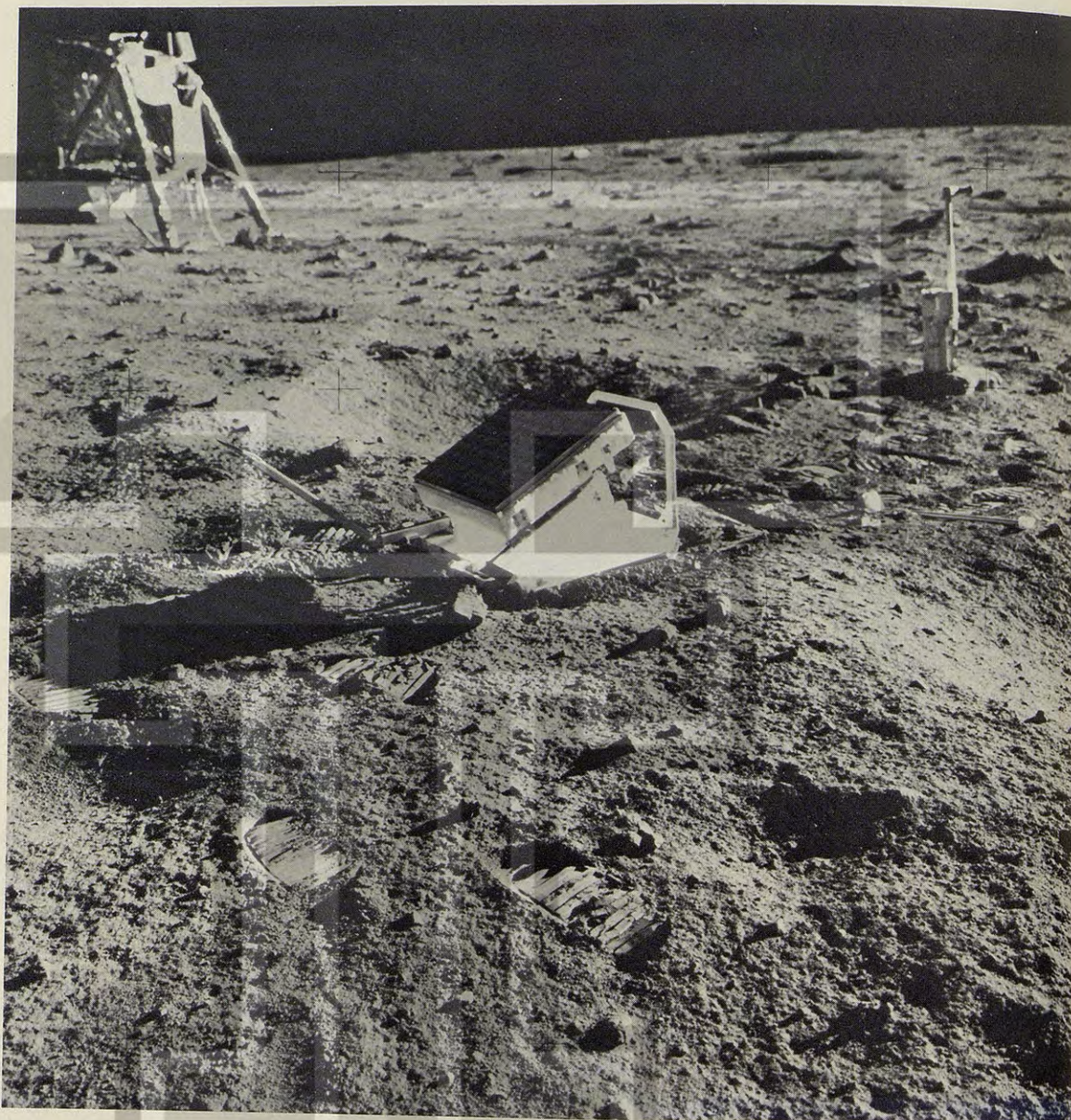


FIGURE 7-7. — The LRRR deployed on the Moon.

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 sec of arc divergence.

Techniques for pointing such narrow beams to a specific location on the Moon were developed

during the successful Surveyor 7 laser-beam-pointing tests (ref. 7-7). 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 the f -number, the collimated beam was projected to the selected location on the Moon and detected by the television camera on the Surveyor

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FIGURE 7-8. — View of the Moon through the McDonald Observatory telescope showing the alignment of the laser beam.

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 the image of the Moon and the laser light intercepted by the telescope corner reflectors into the guiding system (ref. 7-8).

A view of the region of the Moon around Tranquility Base is shown in figure 7-8, which was taken through the guiding eyepiece of the McDonald Observatory 107-in. telescope. The reticle marks used to guide from craters are clearly shown, along with the intercepted laser light. In final alinement, the small circle is made to coincide with both Tranquility Base and the

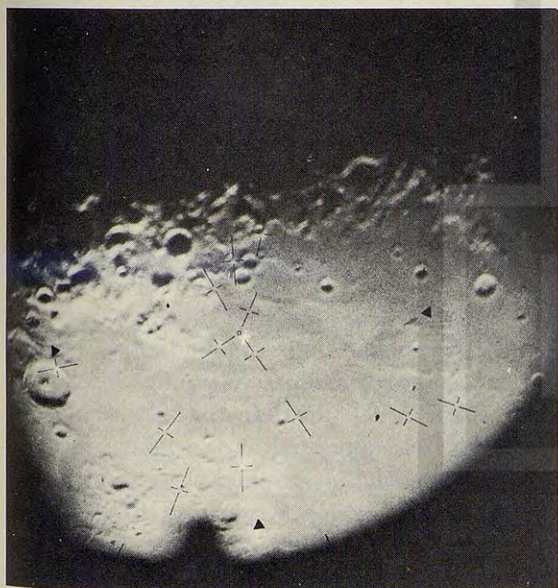


FIGURE 7-8. — View through guiding eyepiece of the McDonald Observatory 107-in. telescope during process of alinement.

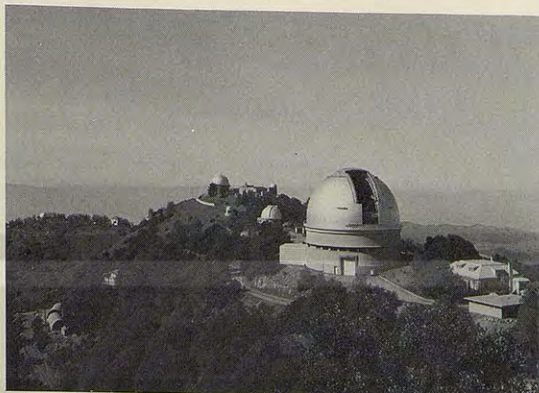


FIGURE 7-9. — Lick Observatory, University of California, at Mount Hamilton, California.

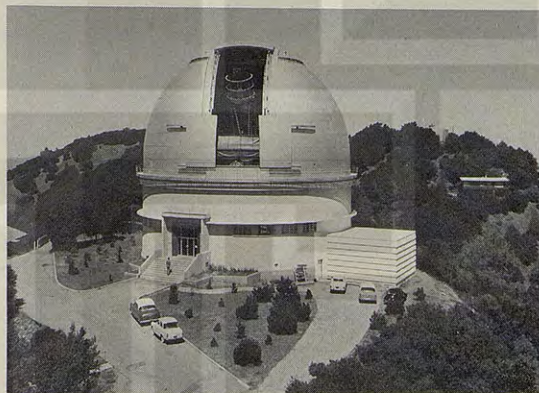


FIGURE 7-10. — Lick Observatory 120-in. telescope dome.

center of the laser spot. The large size of the laser spot is caused by imperfections in the telescope corner reflectors, not by beam divergence. The diameter of the reticle circle is approximately 3.6 seconds of arc. Many craters are not resolved because of poor seeing conditions at the time the photograph was made.

Figures 7-9 to 7-14 are views of the Lick Observatory, University of California, at Mount Hamilton, California; the Lick Observatory 120-in. telescope, the second largest in the world; the McDonald Observatory, University of Texas, at Mount Locke, Tex.; and the McDonald Observatory 107-in. telescope, the third largest in the world. Lasers were mounted in a stationary position at a coudé focus of each instrument.

The Lick Observatory participated in the acquisition phase of the experiment to increase



FIGURE 7-11. — Lick Observatory 120-in. telescope.



FIGURE 7-12. — McDonald Observatory, University of Texas, at Mount Locke, Tex.

the probability of getting early returns because the weather and seeing there are generally excellent in the summer. Returns at the Lick Observatory, which is no longer in operation, were observed on August 1 and 3, 1969. The McDonald Observatory is equipped to make daily range measurements, weather permitting, for years. Re-

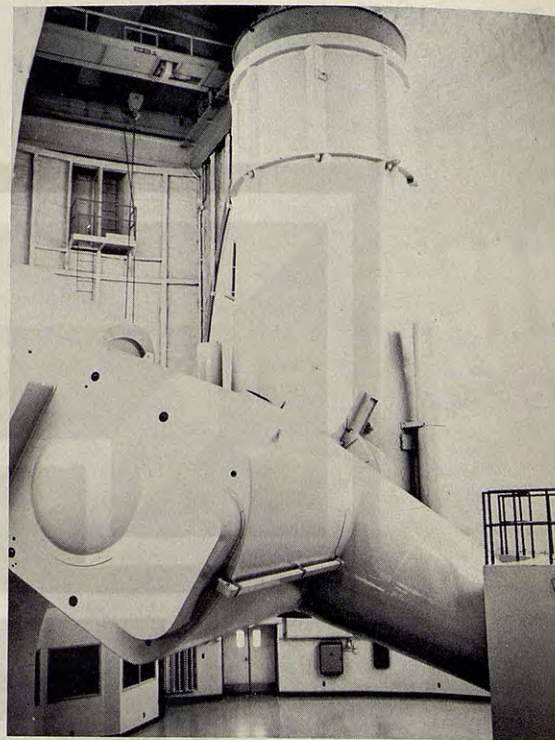


FIGURE 7-13. — McDonald Observatory 107-in. telescope.

turns were observed on August 20, September 3, September 4, and September 22, 1969, at the McDonald Observatory.

Observations at the Lick Observatory

System A

The ranging system at the Lick Observatory consisted of a giant-pulse, high-powered ruby laser (operated at the coudé focus) which was optically coupled through the 120-in. telescope and could be fired at 30-sec intervals. The angular diameter of the outgoing beam was approximately 2 seconds of arc and made a spot of light on the Moon approximately 2 miles in diameter. The return signal was detected by a photomultiplier that was mounted at the coudé focus behind a 10-second-of-arc 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 (TDG), initiated by the firing of the laser, was used to activate the acquiring electronics approximately 2.5 sec (the Earth-Moon round-trip time for light) later. The

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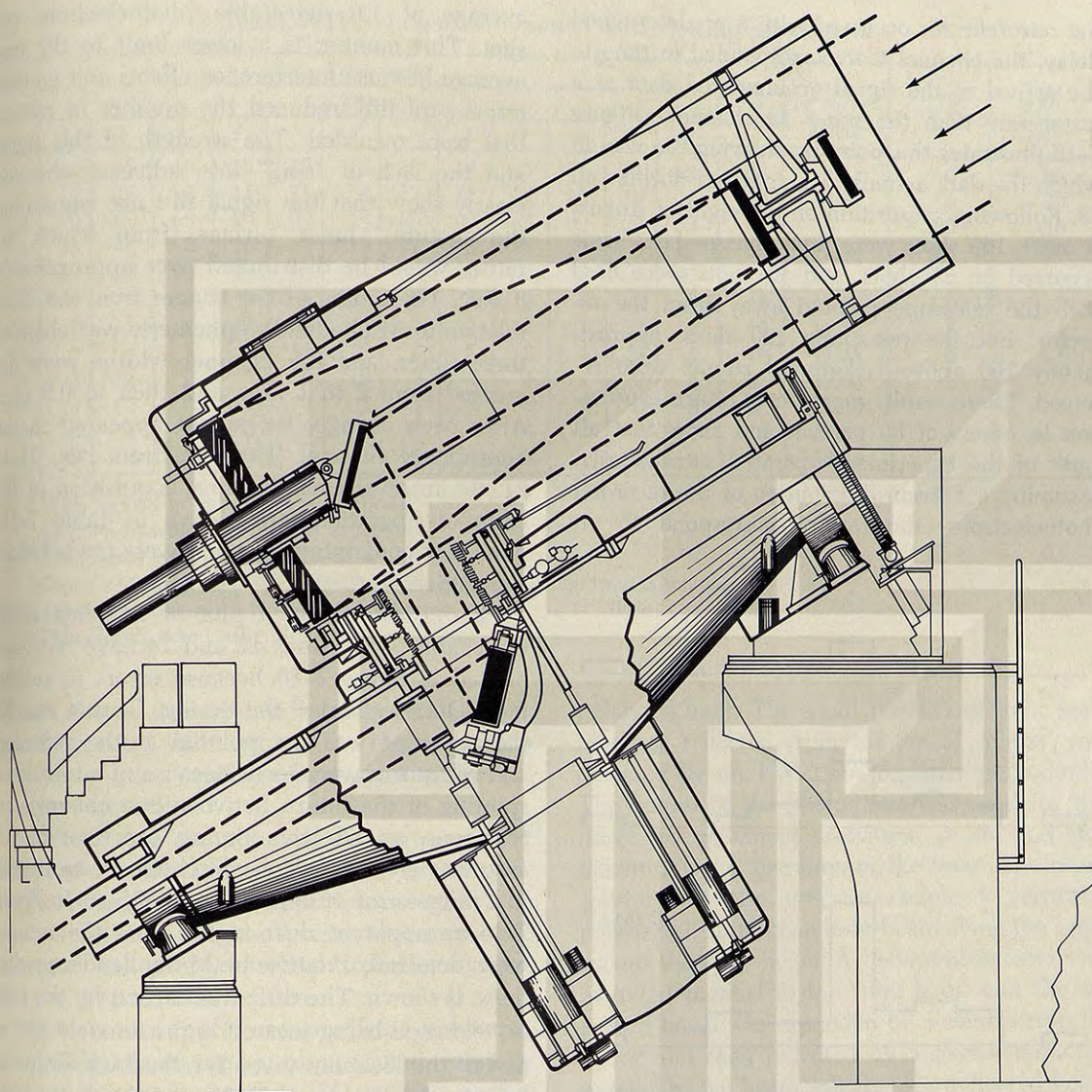


FIGURE 7-14. — Optical path in the McDonald Observatory 107-in. telescope.

delay generator was set for each shot by using the LE 16 ephemeris. (See the section of this report entitled "The Lunar Ephemeris: Predictions and Preliminary Results.")

Following the pulse produced by the TDG, the output pulses from the photomultiplier were channeled sequentially into 12 binary scalars. Each scalar channel had a dwell time that was adjustable from 0.25 to 4 μsec (ref. 7-8). The routing of the pulses to the scalars 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 scalars 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 scalar cycling following a laser firing, a small online computer read the contents and reset the scalars. The computer stored the accumulated count for each of the scalars 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 retroreflector occurred with a predetermined delay, the channel that corresponded in time to the arrival of the signal accumulated data at a faster rate than the other 12 channels. Figure 7-15 illustrates this point by showing the way in which the data actually accumulated during run 18. Following acquisition on the night of August 1, 1969, 169 shots were fired. 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. These results represent a return expectation in excess of 80 percent and show that all parts of the experiment operated satisfactorily. Assuming a Poisson distribution of the recorded photoelectrons, the returns correspond to an

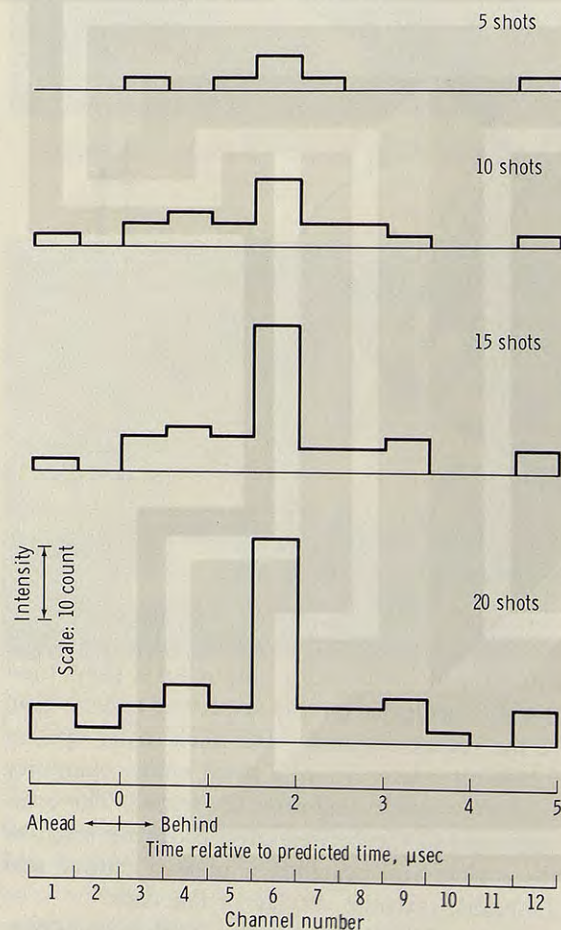


FIGURE 7-15. — Histogram showing the growth of the retroreflected signal in channel 6.

average of 1.6 detectable photoelectrons per shot. This number is a lower limit to the true average because interference effects and guiding errors probably reduced the number of returns that were recorded. The strength of this signal and the lack of "spill" into adjacent channels clearly show that the signal did not come from the "natural" lunar surface, from which the return would be distributed over approximately 8 μ sec. The timing of the trigger from the TDG relative to Mulholland's ephemeris was changed three times, and the channel widths were decreased from 2 to 1 μ sec and then to 0.5 μ sec. After each change, the signal appeared in the appropriate channel. The data from runs 10 to 21, the interval from the first acquisition to the close of operation, are shown in table 7-IV. Nine runs containing 162 shots were made before acquisition.

Figure 7-16 shows a plot of the data taken from table 7-IV. Runs 12 and 14 have not been plotted in figure 7-16 because errors in setting the TDG 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 runs, an effective timing precision of 0.1 μ sec was achieved. This precision is equivalent to a range error of approximately 15 m. In figure 7-16 an apparent drift in the time the returns were detected, relative to Mulholland's predictions, is shown. The drift was caused by the 120-in. telescope being located approximately 524 m east of the locations given for the Lick Observatory in the American Ephemeris and Nautical Almanac. A curve showing this correction to the original ephemeris is given in figure 7-16. Translation of this curve along the ordinate is allowable, and the amount of time gives the difference between the observed range and the predicted range. When the correct coordinates are used, the observations agree with the predicted curve.

System B

The primary function of acquisition system B at the Lick Observatory was to locate the deployed LRRR in range and position. System B was not intended to satisfy the long-term objectives of the lunar ranging experiment; however,

Run	1	2	3
10	12	8	1
11	12	12	1
12	(c)	(c)	(c)
13	13	8	
14	(c)	(c)	(c)
15	4	3	
16	1	1	
17	6	3	
18	3	1	
19	3	3	
20	2	1	
21	5	2	

^a With respect to

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TABLE 7-IV. Log of observation data showing acquisition

Run	Total counts												No. of shots	u.t. for middle of run, hr:min	Channel width, μsec	Time of first channel ^a μsec
	Channel															
	1	2	3	4	5	6	7	8	9	10	11	12				
10	12	8	16	18	12	14	10	17	13	^b 27	12	12	20	10:21	2.0	−20
11	12	12	12	11	11	6	13	11	14	^b 26	10	14	14	10:32	2.0	−20
12	(c)	(c)	(c)	(c)	(c)	(c)	(c)	(c)	(c)	(c)	(c)	(c)	16	—	2.0	−10
13	13	8	8	12	7	^b 18	11	5	6	7	8	12	13	11:04	2.0	−10
14	(c)	(c)	(c)	(c)	(c)	(c)	(c)	(c)	(c)	(c)	(c)	(c)	6	—	1.0	−10
^d 15	4	3	3	5	4	^b 17	6	8	10	5	6	8	18	11:23	1.0	−5
16	1	1	2	2	^b 6	3	3	1	2	1	3	2	10	11:36	.5	−1
17	6	3	4	2	^b 11	^b 9	2	7	2	4	2	5	16	11:45	.5	−1
18	3	1	3	5	3	^b 19	3	3	4	1	0	4	22	12:03	.5	−1
^e 19	3	3	3	10	4	3	5	2	5	5	8	5	22	12:19	.5	−1
^f 20	2	1	1	0	3	4	^b 6	2	4	2	2	4	10	12:23	.5	−1
21	5	2	2	3	2	1	^b 12	^b 11	3	4	5	2	22	12:45	.5	−1

^a With respect to ephemeris predictions.^b Channel in which return was expected.^c Range-gate errors invalidated data.^d Data from three shots with erroneous range gates deleted from tabulation.^e Telescope pointed 16 km south of reflector.^f Thin clouds noted near Moon.

System B was designed to be a sensitive, moderately precise, semiautomatic, high-repetition rate system using existing off-the-shelf equipment wherever possible.

System B was composed of several essentially independent subsystems. These subsystems were the laser-transmitter/power-supply assembly, the receiver-detector ranging system, the range gate generator and data control and recorder system, and the time standard system.

The laser transmitter uses oscillator and amplifier heads employing a conventional rotating-prism, bleachable-absorber, "Q-switch" mechanism. The oscillator and amplifier heads are identical and use 110-mm-long, 15-mm-diameter Brewster-Brewster rubies. An existing laser system that was modified for this program was capable of operation at 10 J at 3-sec intervals with a pulse width of 60 to 80 nsec.

For operation at the Lick Observatory, modification of the laser system required the incorporation of all normal transmit-receive ranging functions and of a boresight capability onto the laser case. An optical-mechanical assembly (fig. 7-17) was designed to be attached to the laser case. The exiting laser beam passed through a beam splitter, which was oriented at Brewster's angle for minimum reflection of horizontally

polarized light. The small fraction of light scattered or reflected from the beam splitter was detected by an FW 114A biplanar photodiode. The output of the photodiode was used for the range measurement initiation pulse and for monitoring the operation of the laser. The beam splitter was also used to couple a vertically polarized helium-neon laser beam along the same axis as the ruby beam. A helium-neon laser was mounted parallel to the ruby laser, and the resultant beam was expanded by a small autocollimator and then reflected by a mirror mounted parallel to the beam splitter. The reflected beam was then rereflected by the beam splitter along the laser axis. The laser produced an elliptical cross-section beam that was corrected and expanded to 50 mm in diameter by the Brewster entrance prism telescope. The 50-mm exit beam was reflected at right angles onto a 50-mm-aperture F39 lens that was positioned at the appropriate place with respect to the coudé focus of the 120-in. telescope optical system.

The returning energy follows essentially the same path as the transmitted energy. A flip mirror, actuated by a small solenoid, reflects the returning signal after the signal is passed through the correcting telescope to a field-limiting lens and aperture. The aperture in the field-limiting

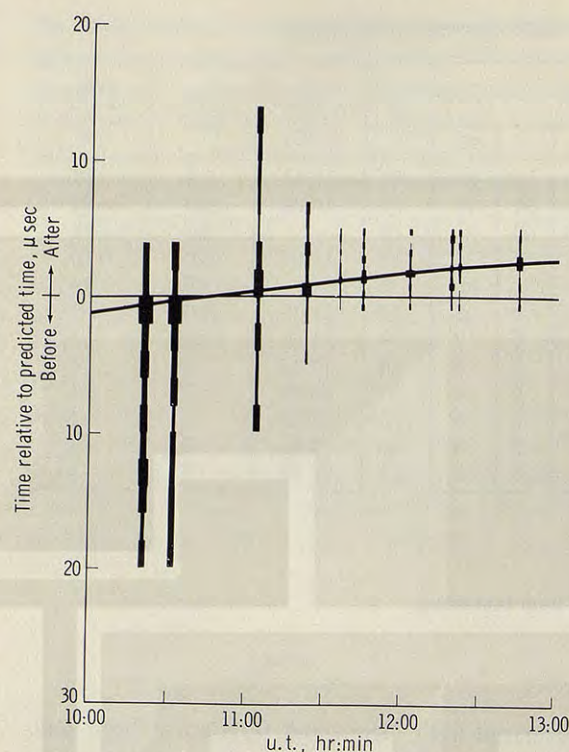


FIGURE 7-16. — Three-dimensional figure showing the time of the run (abscissa), the range window during which the equipment was open for receiving data (ordinate), and the number of counts in each channel (width of the bar). It is clear that in each run in which returns were expected they were seen in the correct channel. During run 19 (third from right-hand end), the telescope was pointed away from the reflector, and no returns were seen.

system is sized for a 10-second-of-arc field of view in space. Light passing through the aperture is collimated and passed through a 2.7-Å bandpass filter. The light is divided into two equal beams by a dividing prism; then, the beams of light enter the enhancement prism on each of the two photomultipliers.

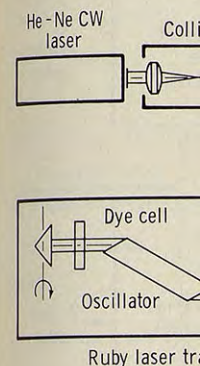
Two detectors (operating in coincidence) and a range gate were used to eliminate as much extraneous background noise as possible. Type 56 TVP photomultipliers used enhancement prisms to allow multiple reflection of the entrance light from the photocathode. The output of each photomultiplier tube was discriminated and shaped with an EGG T105/N dual discriminator. Because theoretical considerations indicate that only a few photoelectrons occur for each

transmitted pulse, the discriminator was used to stretch each detected pulse by the length of the transmitted pulse. A coincidence overlap equal to the transmitted pulse duration was necessary because, lacking discrimination, a photoelectron from each photomultiplier tube could be related to any time within the transmitted pulse duration. The outputs of the discriminators were AND'ed in the EGG C102B/N coincidence module.

The actual range measurement (fig. 7-18) was made with a 1-nsec time-interval counter. The time-interval counter was started by the photodiode output each time the laser transmitter operated. The discriminators and the stop channel of the time-interval unit were disabled by the range gate until the expected time of arrival of the reflected laser pulse. If both photomultiplier tubes detected a photoelectron within the coincidence resolving time of the EGG C102B/N, the output would stop the time-interval unit.

The photodiode signal was used in two other measurements. First, the signal was used to stop a 100-μsec-resolution time-interval unit that was started by the "ontime" timing signal from the real-time clock. This measurement determined the time, to the nearest 100 μsec, of the range measurement. The pulse was also converted, monitoring the overall performance of the laser during the operation.

System B was controlled and operated by a special digital logic assembly. This device (fig. 7-19) generated laser fire signals and the range gate window, sampled all measurement devices for information, and recorded the information. One of the most important aspects of the operation is the generation of the range gate window, based on knowledge of where the retroreflectors should be. Furthermore, because this information may not be as accurate as required, it is necessary to change the information essentially in real time. The range gate window was generated with an externally, as well as manually, programmed delay pulse generator. The programmed input for the delay pulse generator was obtained from a lunar prediction drive tape containing the expected round-trip time interval to the lunar surface for every 3 sec of time. A digital comparison between the command time on the tape and real time was made to maintain the tape in



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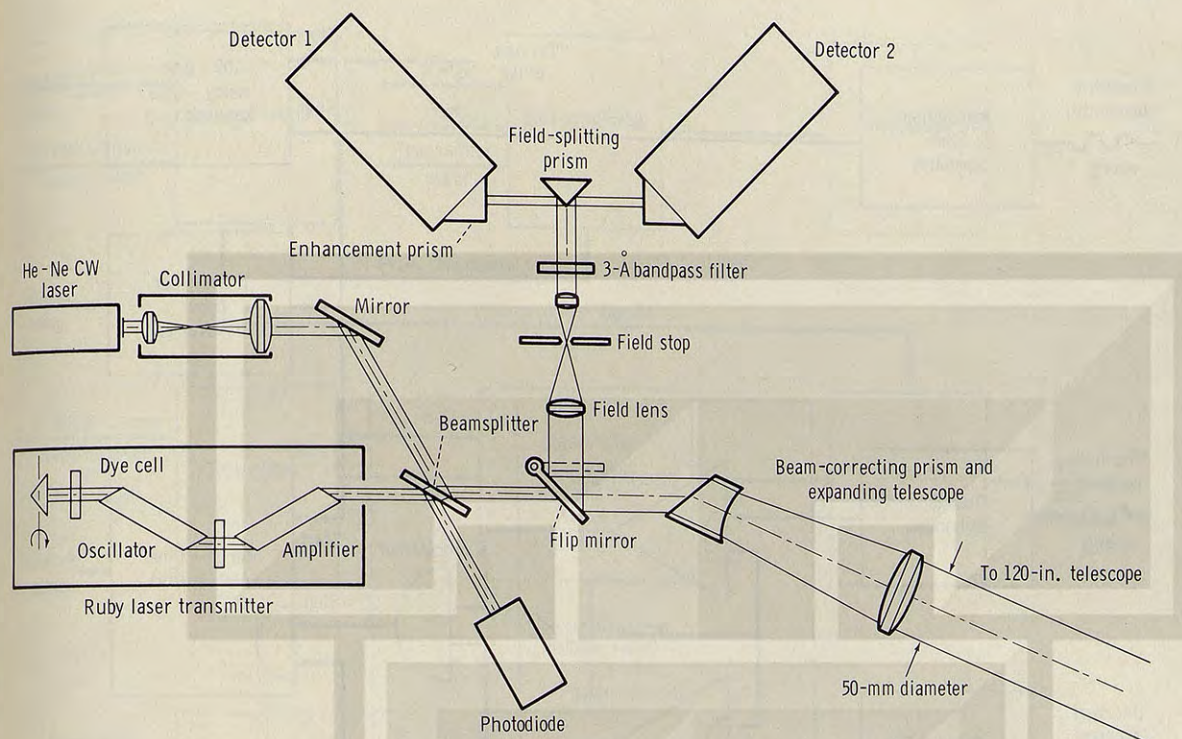


FIGURE 7-17. — Optical schematic of system B at Lick Observatory.

synchronization with real time. The range information on the tape was then stored and transferred to the delay pulse generator prior to each laser firing. The laser firing started the delay pulse generator; and after the predicted delay, a pulse initiated the range-gate-window pulse generator. The range-gate-window length was variable and was used to enable the detector discriminators and the range time-interval unit at the time a return signal was expected.

The measured data were recorded with a multiplexing data gate and standard line printer. The control section generated print commands for each series of measurements at the correct time during the 3-sec cycle period. The control section obtained timing signals from the time standard rack (fig. 7-20). Real time was maintained to an accuracy of $\pm 10 \mu\text{sec}$ during the operation, by comparing signals from the Loran C chain with the real-time clock using the Loran C synchronization generator.

The system was operated for a period of 1 hr and 45 min on the morning of August 3, 1969, during which the laser was fired 1230 times.

The total number of apparent measured ranges during this period was 98. The low number of returns relative to the number of transmitted pulses is related to a slight (2 sec of arc) misalignment in the detector optical system and to the failure of the delay pulse generator to operate in the externally programed mode. Furthermore, because returns were not immediately recognized, an angle search was made over a longer time period.

The measured range time could have three possible sources: a return from the retroreflector, a return from the lunar surface, or random noise coincidence from reflected sunlight and background. Statistically, 35 to 50 noise coincidences and approximately 30 lunar surface ranges would be expected in 1200 firings. Because the numbers agree, within acceptable limits, with the total number measured, it is not obvious that returns from the retroreflectors were measured. However, any returns from the retroreflectors should fall within the precision of the system or within 100 nsec with respect to the true range to the package.

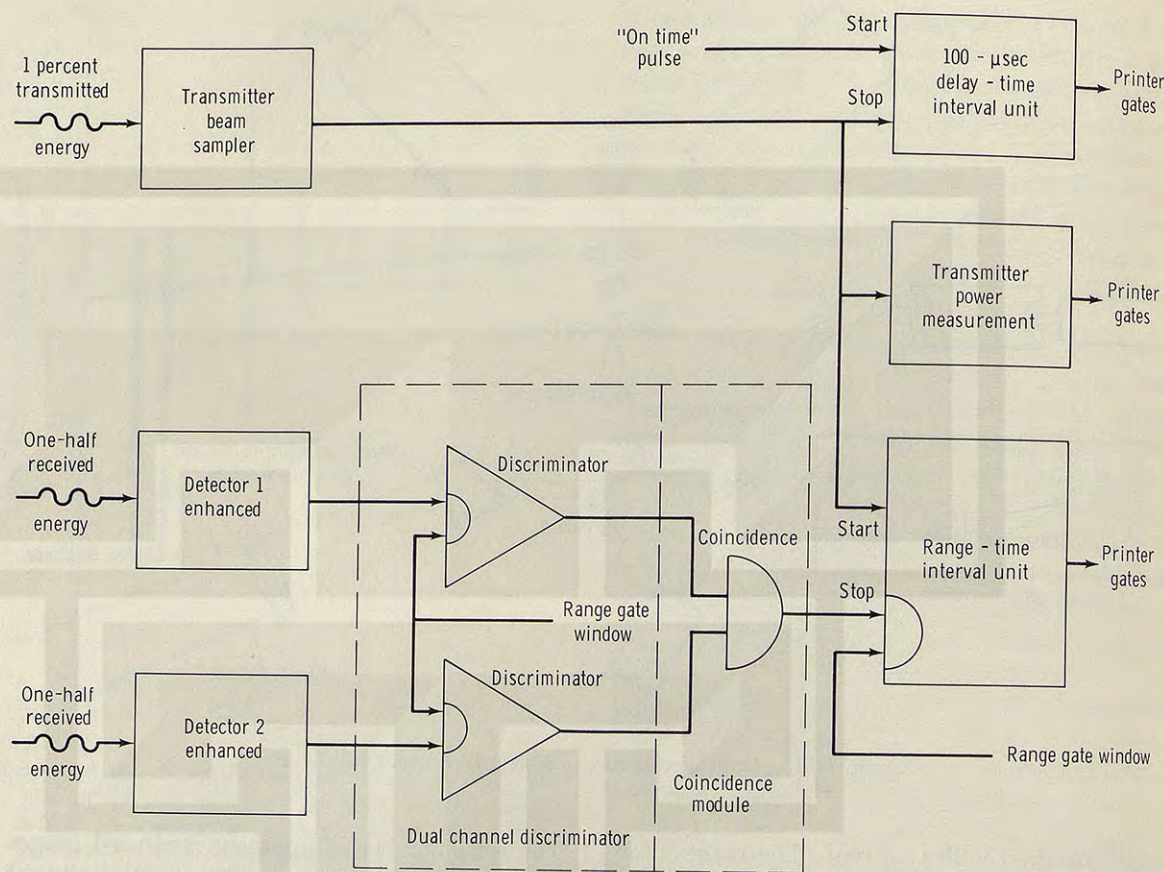


FIGURE 7-18. — Receiver and ranging section.

The observed range time measurements were compared arithmetically with the predicted range time and then linearly corrected because of a known parallax error. The parallax error occurred because a different site was used for the range predictions. The linear correction was performed by taking the initial range residuals and fitting (in a least squares sense) a first-order polynomial to the residuals. Then, only those residuals occurring within a certain range of the polynomial were used to redefine the polynomial. This technique was used successively three times to generate a polynomial about which 11 of the measured ranges had a root mean square of 45 nsec. Furthermore, because of the parallax error, the coefficients of the polynomial agree with the expected deviations from the predicted range.

The range residuals corrected to this linear equation were used to construct a histogram (fig. 7-21) with 100-nsec intervals from -5 to $+5$

μ sec. The data lying outside of the $\pm 5 \mu$ sec were not displayed because no interval contained more than one point and because no significant bunching was observed. The histogram clearly shows a central peak that cannot be supported by any statistical interpretation other than one assuming returns from the retroreflector.

Observations at the McDonald Observatory

The laser in use presently is a custom-built two-stage pockels-cell switched ruby system. Typical operating conditions were as follows:

- (1) Energy: 7 J
- (2) Pulse width: 20 nsec
- (3) Beam divergence: 2.4 mrad (measured at full energy points)
- (4) Repetition rate: once every 6 sec
- (5) Wavelength: $6943.0 \pm 0.2 \text{ \AA}$ at 70° F
- (6) Amplifier rod diameter: 0.75 in.

The detector package had a multiplier that had a maximum efficiency of 5 percent at 6943 $\text{\AA}$. The package had 80 000 counts per second dry ice (as during the Apollo 11 mission) current was 10 000 counts per second. Both filters were 1/2 inch holes restricting the light to 6" or 9" were covered by a protective shutter. The laser firing, opening the shutter around the time of the firing, efficiency of the vacuum tube electrons produced a sharp scope aperture (1/2 inch) telescope optics, which was used during the Apollo 11 mission.

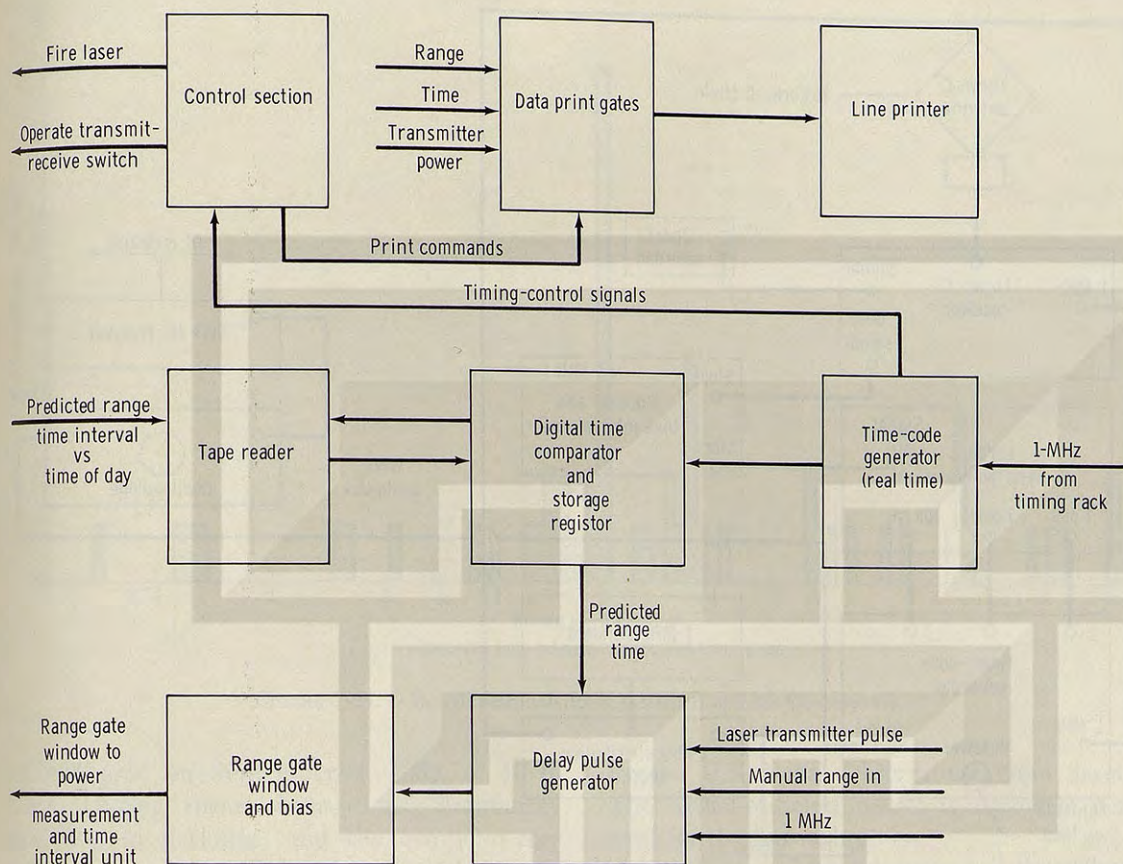


FIGURE 7-19. — Range gate generator and data control.

The detector package contained a photomultiplier that had a measured quantum efficiency of 5 percent at 6943 angstroms and a dark current of 80 000 counts per second. When cooled by dry ice (as during ranging operations), the dark current was 10 000 counts per second. 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" were commonly used. An air-driven protective shutter was closed during the time of laser firing, opening for approximately 1 sec around the time for receiving returns. The net efficiency of the whole receiver, ratio of photoelectrons produced to photons entering the telescope aperture (with a 3-Å filter), including telescope optics, was measured to be 0.5 percent, using starlight from Vega.

The block diagram of the timing electronics used during the acquisition period is shown in

figure 7-22. The electronics consist of a multistop time-to-pulse-height converter (MSTPHC) for coarse range search covering an interval of 30 μ sec with 0.5- μ sec bins (ref. 7-8) in addition to the core circuits forming part of the intended subnanosecond timing system. 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-sec intervals. The online computer read the range prediction, set the range gate TDG, and fired the laser within 1 μ sec of the integral 6-sec epoch. 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- μ sec 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

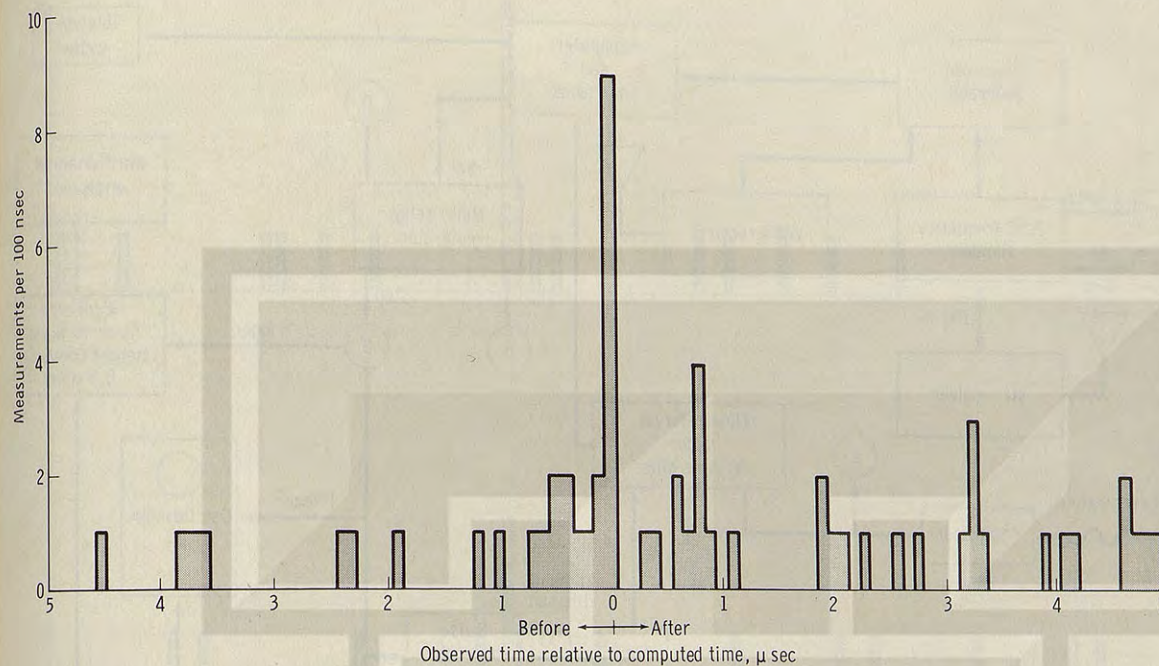


FIGURE 7-21. — Range residuals from system B at Lick Observatory.

797 ± 24 nsec on September 4, 1969, at 10:10 G.m.t. During these observations, Tranquility Base was in darkness, and the computer-controlled drive of the telescope was used successfully to offset from visible craters and track the reflector.

The Lunar Ephemeris: Predictions and Preliminary Results

The fundamental input to the calculation of predictions for the LRRR is the lunar ephemeris, which gives the geocentric position and velocity of the lunar center of mass. An ephemeris is being used that was developed at the Jet Propulsion Laboratory (JPL) and is designated LE 16. This ephemeris is believed to be far superior in the range coordinate to any other extant ephemeris. The available observational evidence is meager but supports this belief. The modeling of the topocentric effects relating to the motions of the observatory and the reflector about the centers of mass of the respective bodies is complete and is similar to that used in JPL spacecraft tracking programs. Universal time (u.t.) 1 is modeled and extrapolated by polynomials fit to the instantaneous determinations

by the U.S. Naval Observatory Time Service. The Koziel-Mitielski model is currently being used for the lunar librations.

Coordinates of the telescope and the reflector package are input variables to the prediction program. Reflector coordinates presently used are those derived at the NASA Manned Spacecraft Center from spacecraft tracking of the lunar module, since this dynamic determination is essentially the inverse of the predictive problem and is, thus, more compatible than the selenographic determinations.

It was anticipated that the topographic modeling would be the primary error source in the earliest phase of ranging operations. This belief was based upon the indications from command and service module (CSM) tracking of Apollo 8 and Apollo 10, both of which indicated LE 16 ephemeris errors of 40 to 50 m ($0.3 \mu\text{sec}$), and is based on the knowledge that various estimates of the selenocentric distances of surface locations disagreed by perhaps 2 km for a specific region. The decision to use the dynamic determinations of the location simplified the real-time processes but did not relieve the radial distance uncertainty until laser acquisition was an accom-

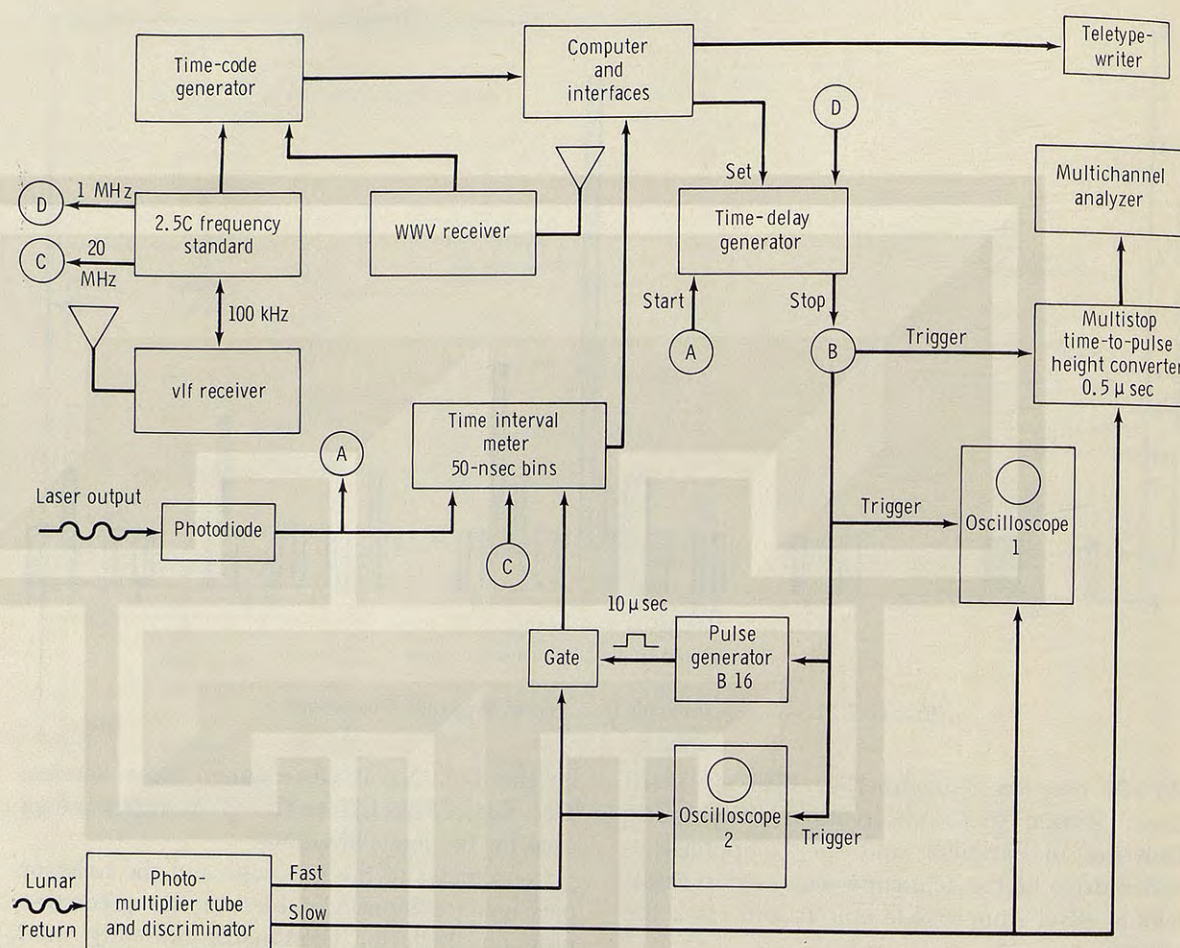


FIGURE 7-22. — Block diagram of McDonald Observatory acquisition and early measurement phase electronics.

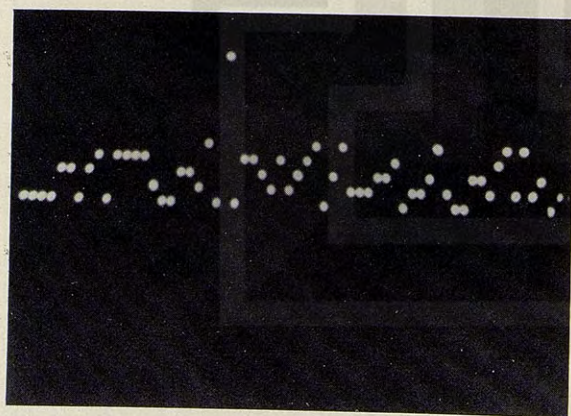


FIGURE 7-23. — MSTPHC display of McDonald Observatory acquisition.

plished fact. As the current "best estimate" of the landing site shifted, predicted ranges were affected by approximately 4 km ($28 \mu\text{sec}$). Site coordinates for Tranquility Base provided by the NASA Manned Spacecraft Center on July 22, 1969, are currently being used.

Tracking information is available on both the CSM and the lunar module during lunar surface operations. The CSM data indicate an ephemeris error not greater than 50 m. Computations of predictions for comparison with the LM ranging data, using the coordinates mentioned previously, show residuals of approximately 2 km, with a drift of 0.3 km in 15 min. The explanation of this anomaly is not yet known, but it seems to be associated with the tracking station location.

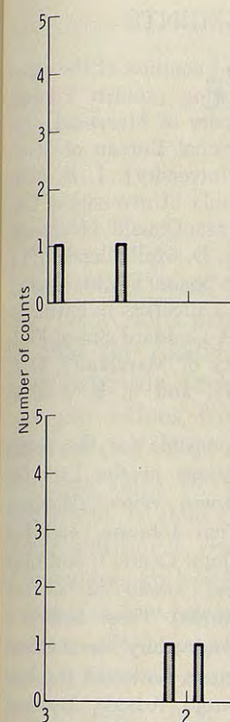


FIGURE 7-24

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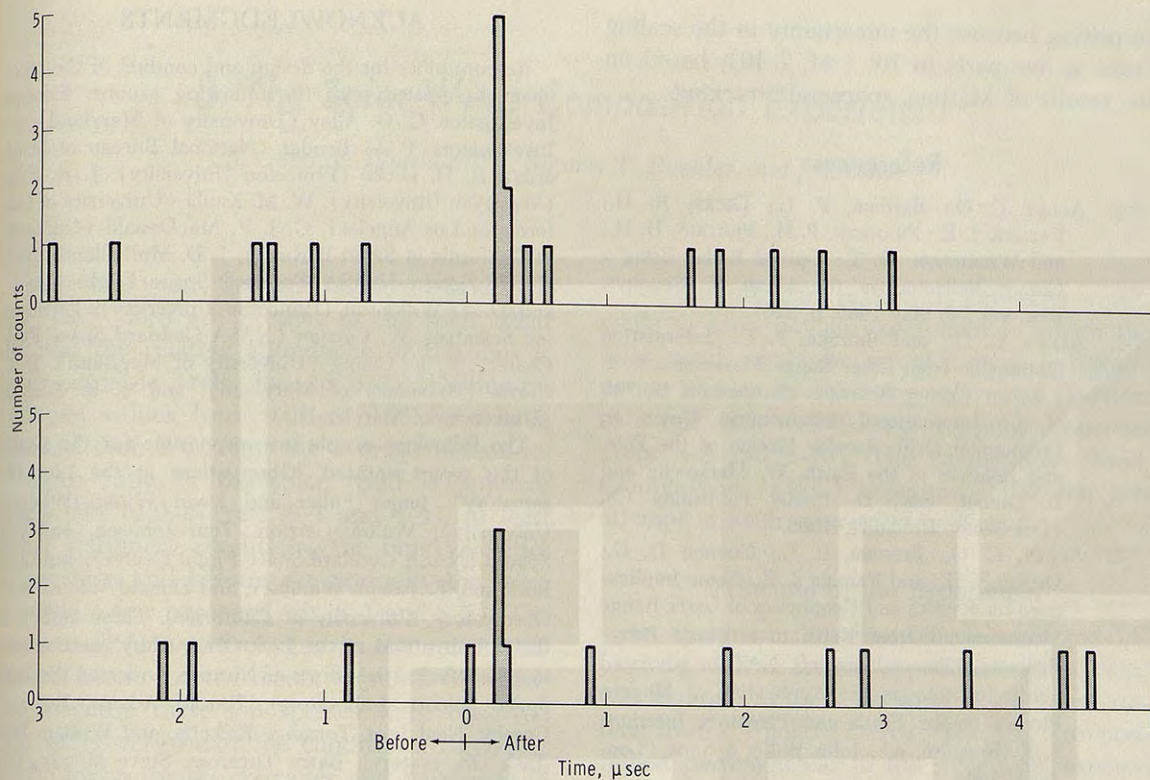


FIGURE 7-24. — Histogram of single-stop TIM readings on two successive 50-shot runs on August 20, 1969, at the McDonald Observatory.

Initial acquisition of the LRRR was accomplished with predictions based on the coordinates of the Lick Observatory, as published in the American Ephemeris and Nautical Almanac. The Lick Observatory 120-in. telescope used in the experiment is actually a distance of approximately 1800 ft from that location, causing drift in the observation residuals. The result of introducing the proper telescope coordinates into the computations is shown in figure 7-25. The residuals relative to the new telescope coordinates appear to be given within $1 \mu\text{sec}$. Figure 7-25 is provisional and subject to later refinement. Within the limitations of figure 7-25, these data are consistent with the subsequent observations at McDonald Observatory.

Although it is premature to discuss the data from the standpoint of any meaningful application, one aspect invites speculation and preliminary inference. The three indirect pseudo-observations (range biases on CSM tracking data)

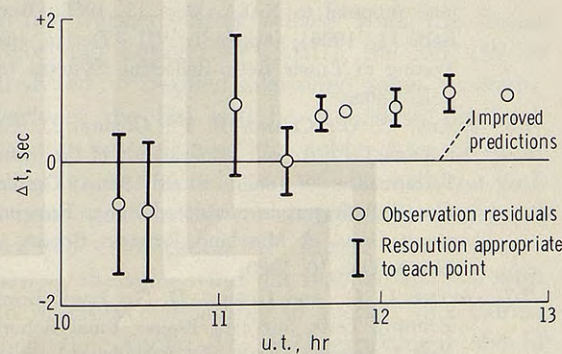


FIGURE 7-25. — Result of using adjusted telescope coordinates for the Lick Observatory. The data are shown for August 1, 1969.

and the first few laser acquisitions yield positive observation residuals. If no observation selection effect is involved, this may be an indication that the ephemeris scaling factor and hence the lunar mean distance requires an adjustment in the seventh place. Such a result would not be

surprising because the uncertainty in the scaling factor is five parts in 10^7 (ref. 7-10), based on the results of Mariner spacecraft tracking.

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ACKNOWLEDGMENTS

Responsibility for the design and conduct of the experiment has rested with the following groups: 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 (JPL), 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).

The following people are responsible for the section of this report entitled "Observations at the Lick Observatory": James Faller and Irwin Winer (Wesleyan University); Walter Carrion, Tom Johnson, and Paul Spadin (NASA Goddard Space Flight Center); and Lloyd Robinson, E. Joseph Wampler, and Donald Wieber (Lick Observatory, University of California). These authors of the "Observations at the Lick Observatory" section wish to acknowledge the efforts of Norman Anderson (Berkeley Space Science Laboratory); Harold Adams, Raymond Greeby, Neal Jern, Terrance Ricketts, and William Stine (Lick Observatory); Barry Tumrose, Steve Moody, Tom Giuffrida, Dick Plumb, and Tuck Stebbins (Wesleyan University); and James MacFarlane, Bill Schaefer, Richard Chabot, James Hitt, and Robert Anderson (NASA Goddard Space Flight Center). Support from funds to the Lick Observatory by NASA grant NAS5-10752 and National Science Foundation grant GP 6310, from funds to Wesleyan by NASA Headquarters grant NGR-07-006-005, and from in-house funds used by Goddard personnel is acknowledged.

The people who are responsible for the section of this report entitled "Observations at the McDonald Observatory" include D. G. Currie, S. K. Poultney, C. O. Alley, E. Silverberg, C. Steggerda, J. Mullendore, and J. Rayner (University of Maryland); H. H. Plotkin and W. Williams (NASA Goddard Space Flight Center); and Brian Warner, Harvey Richardson, and B. Bopp (McDonald Observatory). The authors of this section wish to acknowledge the efforts of Harlan Smith, Charles Jenkins, Johnny Floyd, Dave Dittmar, Mike McCants, and Don Wells (McDonald Observatory); Faust Meraldi, Norris Baldwin, Charles Whitted, and Harry Kriemelmeyer (University of Maryland); and Jim Poland, Peter Minott, Cal Rossey, Jim Fitzgerald, Walter Carrion, Mike Fitzmaurice, and Herb Richard (NASA Goddard Space Flight Center).

Support for the activities at the McDonald Observatory from NASA Grant NGR 21-002-109 to the University of Maryland and from in-house funds at the Goddard Space Flight Center is acknowledged.

J. D. Mulholland (JPL) is responsible for the section entitled "The Lunar Ephemeris."

For several years, that $^4\text{He}^{2+}$ ions are and that the relative highly variable (refs hydrogen values from observed (ref. 8-1), hydrogen ratio in the approximately 0.04 to 0.05 (r during stationary con of hydrogen and heli to within a few percent presence of ^3He and has also been reported ever, because these i only under very favor can be given for the their abundance.

Plasma and magnetic Explorer 35 have est approximation, the M obstacle to the solar v a bow shock has been (8-8). Thus, during the solar-wind particles ca surface of the Moon v energies. The grains material contain great Consequently, it shou valuable information o solar wind from analy material. However, the c is a solar-wind collecto integrating the flux ov time during which rel are probably changed fusion losses and satur tion on short-time varia solar-wind particles in material; thus, the po netic processes influen sition cannot be asses only from lunar surfac

8. The Solar-Wind Composition Experiment

J. Geiss, P. Eberhardt, P. Signer, F. Buehler, and J. Meister

For several years, the fact has been established that $^4\text{He}^{2+}$ ions are present in the solar wind and that the relative abundance of the ions is highly variable (refs. 8-1 to 8-3). Helium-to-hydrogen values from 0.01 to 0.25 have been observed (ref. 8-1), but the average helium-to-hydrogen ratio in the solar wind is approximately 0.04 to 0.05 (refs. 8-1 and 8-4). At least during stationary conditions, the bulk velocities of hydrogen and helium are normally the same to within a few percent (refs. 8-1 and 8-5). The presence of ^3He and oxygen in the solar wind has also been reported recently (ref. 8-6). However, because these ion species were observed only under very favorable conditions, no values can be given for the averages and variations of their abundance.

Plasma and magnetic field measurements of Explorer 35 have established that, to a good approximation, the Moon behaves like a passive obstacle to the solar wind, and no evidence for a bow shock has been observed (refs. 8-7 and 8-8). Thus, during the normal lunar day, the solar-wind particles can be expected to reach the surface of the Moon with essentially unchanged energies. The grains of the fine lunar surface material contain great amounts of these particles. Consequently, it should be possible to extract valuable information on the composition of the solar wind from analyses of lunar surface material. However, the dust on the lunar surface is a solar-wind collector of uncertain properties, integrating the flux over an unknown period of time during which relative element abundances are probably changed significantly by both diffusion losses and saturation effects. No information on short-time variations can be derived from solar-wind particles implanted in lunar surface material; thus, the possibility that hydromagnetic processes influence the solar-wind composition cannot be assessed from data obtained only from lunar surface-material analysis.

For the foregoing reasons, it appeared worthwhile to carry out an experiment in which the solar wind would be sampled over a definite period of time by collecting solar-wind particles in a foil with well-defined trapping properties (refs. 8-9 and 8-10). The Apollo Solar-Wind-Composition (SWC) experiment was the first attempt at such solar-wind collecting.

Principle of the Experiment

An aluminum foil sheet 30 cm wide and 140 cm long with an area of approximately 4000 cm² was exposed to the solar wind at the lunar surface by the Apollo 11 crew. The foil was positioned perpendicular to the solar rays, exposed for 77 min, and brought back to Earth. Solar-wind particles, arriving with an energy of approximately 1 keV/nucleon, are expected to have penetrated approximately 10⁻⁵ cm into the foil, and a large fraction are expected to be firmly trapped. After release from the Lunar Receiving Laboratory (LRL), the foil will be analyzed for trapped solar-wind noble-gas atoms. Parts of the foil will be melted in ultrahigh vacuum systems, and the noble gases of solar-wind origin thus released will be analyzed with a mass spectrometer for element abundance and isotopic composition. If, during the exposure period, the solar wind has reached the foil with an intensity comparable to average flux values, then the Apollo 11 SWC experiment should allow an assessment of the abundances and isotopic compositions of helium, neon, and argon, despite the relatively short exposure time.

Instrumentation and Lunar Surface Operation

The hardware developed for the deployment of the foil carried on the lunar module (LM) descent stage Modularized Equipment Stowage Assembly is shown in figure 8-1. The hardware consists of a five-section telescopic pole and an

aluminum foil screen rolled up on a reel. In the outbound configuration, the reel is stored inside the collapsed pole. The total weight is 0.95 lb. For deployment, the telescopic pole is extended, and the five sections lock automatically. The reel is then pulled out, and the foil is unrolled and fastened to a hook near the lower end of the pole. The reel is spring loaded to facilitate rewinding of the foil on the reel. The pole is pressed upright into the ground. Figure 8-2 shows the instrument as deployed by Astronaut Edwin E. Aldrin, Jr., at the lunar surface during the Apollo 11 extravehicular activity period. When figure 8-2 was photographed, the Sun was approximately 13° above the lunar horizon. One hr and 17 min later, Astronaut Neil A. Armstrong rolled up the foil on the reel. The foil (weight, 0.28 lb) was then detached from the telescopic pole, placed into a Teflon bag, and carried back to Earth inside the Apollo lunar sample return container, which also contained the documented sample.

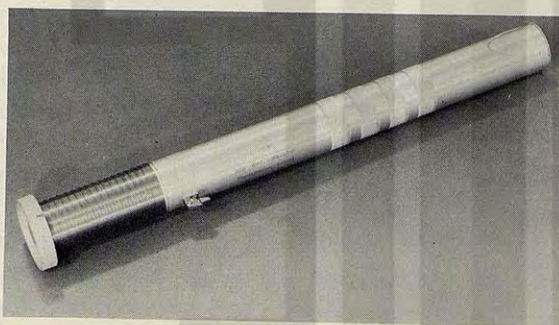


FIGURE 8-1. — Solar-Wind Composition experiment in stowed configuration ready for installation in the LM.

To eliminate the possibility of contamination of the lunar rocks in the container by the SWC instrument, special precautions were taken. All materials used in the construction of the reel and foil assemblies were analyzed for 13 geochemically important trace elements (lithium, beryllium, boron, magnesium, potassium, rubidium, strontium, yttrium, lanthanum, ytterbium, lead, thorium, and uranium). All concentrations were low enough to be geochemically acceptable.

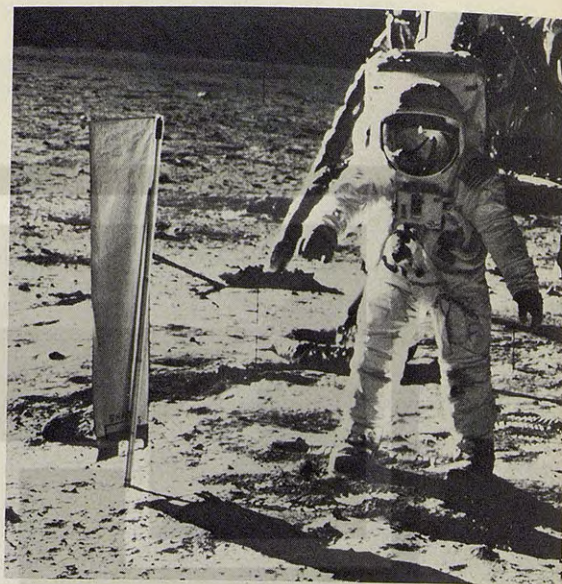


FIGURE 8-2. — Deployed SWC unit with Astronaut Aldrin.

To avoid organic contamination of the lunar surface material inside the container, the instrument was subjected to several heating cycles, and the degree of decontamination was controlled by mass spectrometric analysis. Prior to shipment to the NASA Manned Spacecraft Center and the NASA Kennedy Space Center for installation into the LM, the instrument was double bagged in Teflon and heat sterilized.

The Foil and Its Solar-Wind Trapping Properties

Dimensions and details of the exposed foil assembly are shown in figure 8-3. The main part of the assembly is a $15\text{-}\mu\text{m}$ -thick aluminum foil. The backside of the foil was anodically covered with approximately $1\text{ }\mu\text{m}$ of Al_2O_3 , to keep the foil temperature below 100°C during exposure on the Moon. For reinforcement, the foil was rimmed with Teflon tape.

Test pieces 1, 3, and 5 are foils that were bombarded in the laboratory before the mission with a known flux of neon ions with an energy of 15 keV. The amounts of neon used were large by comparison with the expected solar-wind neon fluxes. Determination of the amount of neon implanted in these test pieces will indicate

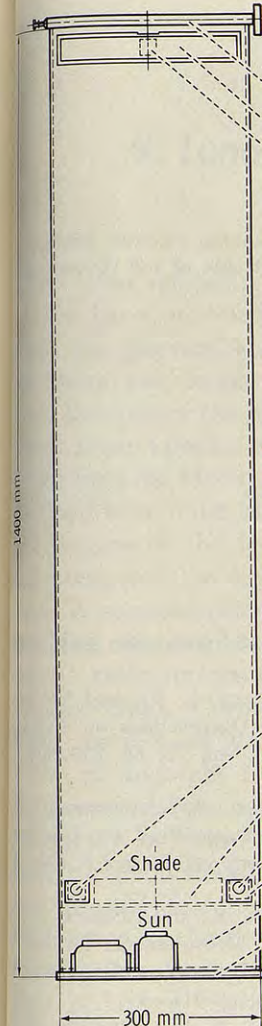


FIGURE 8-3. — Dimensions of the foil assembly.

if solar-wind noble-gas occurred during the mission. Test piece 5 was mounted and remained shielded from the lunar surface; test piece 4 was exposed to the solar wind. A solar-wind flux composite to the Sun was measured in a position that remained shielded from solar wind.

Before flight, the test pieces were placed in foil material for kiloe-



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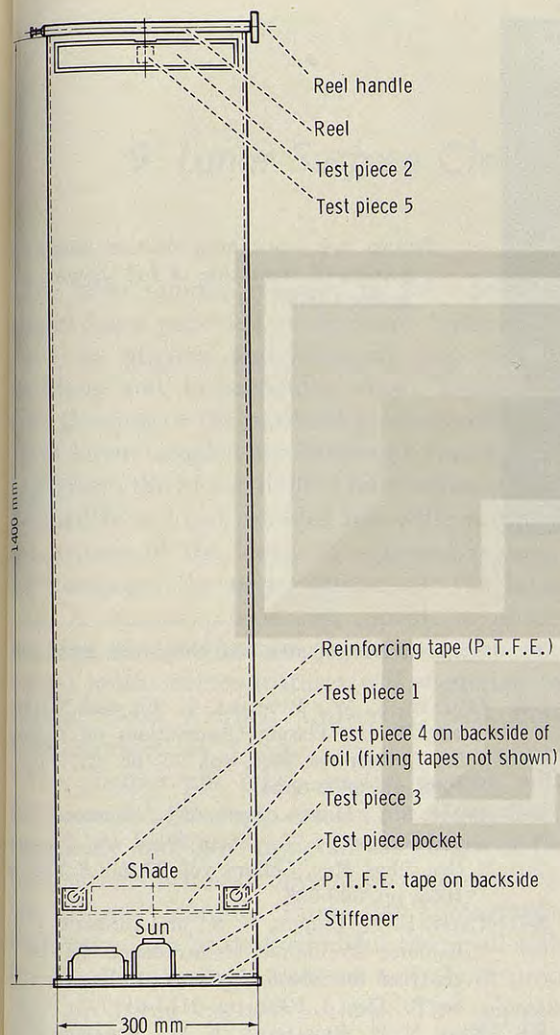


FIGURE 8-3. — Dimensions and details of the exposed foil assembly.

if solar-wind noble-gas losses could have occurred during the mission because of some unexpected diffusion or surface erosion processes. Test piece 5 was mounted in a closed pocket and remained shielded during the exposure on the lunar surface; test pieces 1 and 3 were exposed to the solar wind. Test piece 4 was a piece of foil taped to the backside of the main foil. A solar-wind flux coming from a direction opposite to the Sun could be distinguished by means of test piece 4. Test piece 2 was mounted in a position that remained shielded from the solar wind.

Before flight, the trapping properties of the foil material for kiloelectron-volt ions were ex-

tensively investigated in the laboratory. Trapping probabilities for helium, neon, and argon were determined in a wide energy range. For average solar-wind energies, the probabilities are 89 percent for helium (3 keV), 97 percent for neon (15 keV), and 100 percent for argon (30 keV). Because these figures are only slightly energy dependent, they can be used even if, during exposure, the solar-wind velocity was quite different from the average. The trapping probabilities were found to be independent of foil temperature (20° to 120° C), and they were not affected by simultaneous bombardment with kiloelectron-volt hydrogen ions (H_2^+).

First Laboratory Investigations

The SWC return assembly was kept behind the primary biological barrier in the LRL until the quarantine was lifted, but a 1-ft² portion was cut from the midsection of the foil and sterilized inside a vacuum container by 125° C heat for 39 hr. The vacuum container, with this portion of the foil, was received at Berne, Switzerland, on August 12, 1969. Mass spectrometric investigation of the gas content in the container revealed little air leakage as indicated from the low argon content (3×10^{-8} cc STP ^{40}Ar). However, 10^{-6} cc STP helium and 10^{-8} cc STP neon were found. These gases are interpreted as having leaked, during sterilization, from lunar dust attached to the foil.

With the unaided eye, virtually no dust particles were visible on the foil; however, microscopic investigation disclosed an appreciable number of fine particles. Figure 8-4 shows such dust grains, on the front side of the foil, photographed with a scanning electron microscope.

A few pieces of the foil, with areas of approximately 10 cm² each, were subjected to a cleaning process that included ultrasonic treatments. The noble gases were then extracted and analyzed in mass spectrometers. The presence of helium, neon, and argon was found, and the isotopic composition of these elements was measured. The element abundances and the isotopic compositions were clearly nonterrestrial and generally corresponded to the abundance estimates in the Sun (ref. 8-11) and to estimates derived from measurements taken in gas-rich

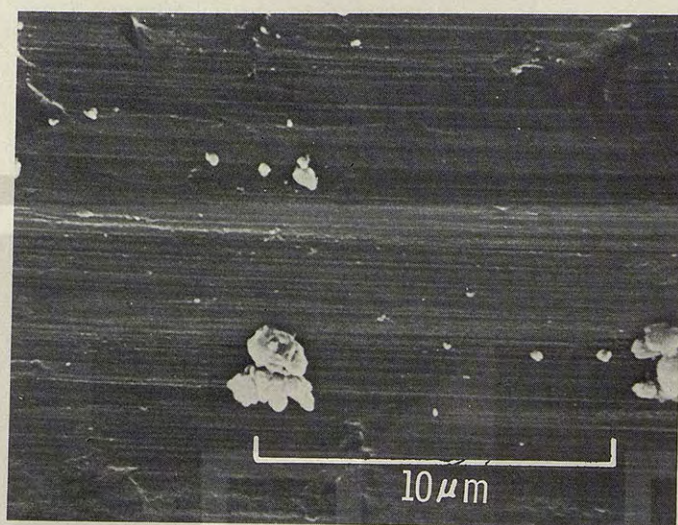


FIGURE 8-4. — Scanning electron microscope picture of front side of foil showing dust grains (4800 $\times$).

meteorites. At the time this report was written, September 8, 1969, various procedures calculated to decrease the dust level on the foil were in process, with the aim of obtaining an unequivocal distinction between solar-wind particles trapped in the foil and noble gases contained in the fine-grained lunar dust particles adhering to the foil.

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9. Lunar

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Apollo Lunar Surfo

The Apollo Lunar S-
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9. Lunar Surface Closeup Stereoscopic Photography

The lunar samples returned by the Apollo 11 mission have provided preliminary information about the physical and chemical properties of the Moon and, in particular, about Tranquility Base. Because of the mechanical environment to which lunar samples are subjected during their return from the Moon, limited information can be obtained from lunar samples about the structure and texture of the loose, fine-grained material that composes the upper surface of the lunar crust. A stereoscopic camera capable of photographing the small-scale (between micro and macro) lunar surface features was suggested by Thomas Gold, Cornell University, and built under contract for NASA.

The photographs taken on the mission with the closeup stereoscopic camera are of outstanding quality and show in detail the nature of the lunar surface material. Several photographs contain unusual features. From the photographs, information can be derived about the small-scale lunar surface geologic features and about processes occurring on the surface. This chapter presents a description of the closeup stereoscopic camera, lists and shows single photos from pairs available for stereoscopic study, and contains an interpretation of the results reported by Professor Gold in *Science*, vol. 165, no. 3900, pp. 1345-1349, Sept. 26, 1969.

Apollo Lunar Surface Closeup Camera

The Apollo Lunar Surface Closeup Camera (ALSCC), built by Eastman Kodak under contract to the NASA Manned Spacecraft Center, was designed to optimize operational simplicity (fig. 9-1). The camera is an automatic, self-powered, twin-lens stereoscopic camera capable of resolving objects as small as $80\text{ }\mu\text{m}$ in diameter on color film. Simplicity of operation was achieved by making the camera focus and the flash exposure fixed and by loading the camera prior to

launch with sufficient Ektachrome MS (S0368) film for the complete mission. To obtain a photograph, an astronaut merely sets the camera over the material to be photographed and depresses the trigger located on the camera handle. When the exposure is complete, the film is automatically advanced to the next frame, and the electronic flash is recharged.

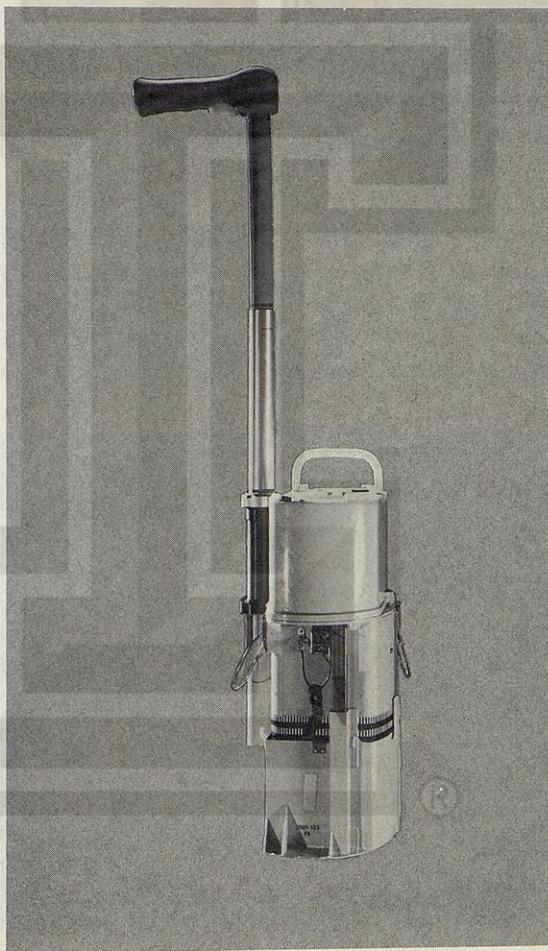


FIGURE 9-1. — Apollo lunar surface closeup camera.

The requirement to simplify the ALSCC operation necessitated a reasonable depth of field that could be achieved only by limiting the image magnification produced by the system. The camera lenses are diffraction-limited 46.12 mm $f/17$ Kodak M-39 copy lenses focused for an object distance of 184.5 mm, providing an image magnification of 0.33. The lenses are mounted 29 mm apart, with their optical axes parallel. The area photographed is 72 mm x 82.8 mm and centered between the optical axes; thus, stereoscopic photographs with a base-to-height ratio of 0.16 are provided (fig. 9-2).

Location of the Stereoscopic Photographs

The specific location at the Apollo 11 lunar landing site where individual stereoscopic photographs were taken cannot be determined with a high degree of confidence. Because of the limited size of the area photographed by the camera, the subject material cannot be identified within the large-scale lunar surface photography. In the scientific debriefing of the Apollo 11

crew, Astronaut Armstrong indicated the general areas, relative to the lunar module, where sequential sets of photographs were taken. Based upon Astronaut Armstrong's comments and the time history of events on the surface, the general locations of the photographs were tentatively established (fig. 9-3).

Description of Photographs

Analysis of the photographic data is not complete and will therefore be published in future documents. For this report, only a preliminary description of four photographs, provided by Gold, is included.

A stereoscopic view (fig. 9-4) shows a close-up of a small lump of lunar surface powder approximately 0.5 in. across, with a splash of glassy material over it. A drop of molten material appears to have fallen on the powder, splashed, and frozen.

Figure 9-5 shows a clump of lunar surface powder with various small, differently colored pieces. Many small, shiny spherical particles can be seen.

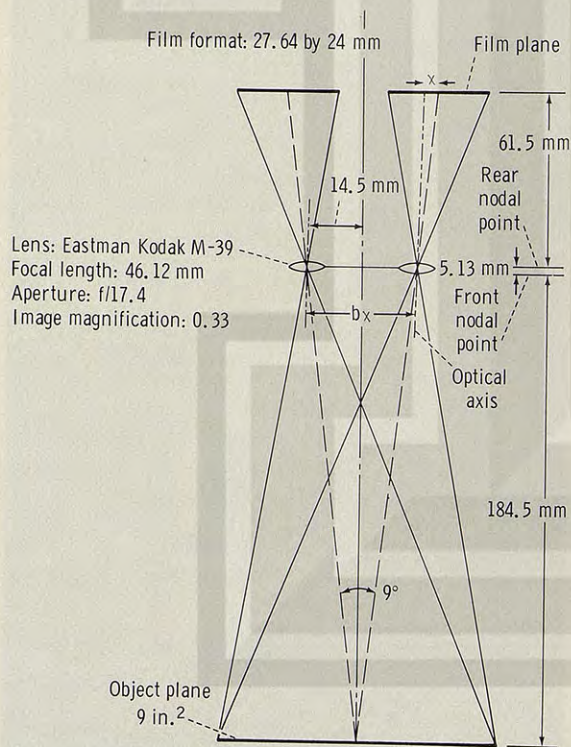


FIGURE 9-2. — Schematic of the ALSCC.

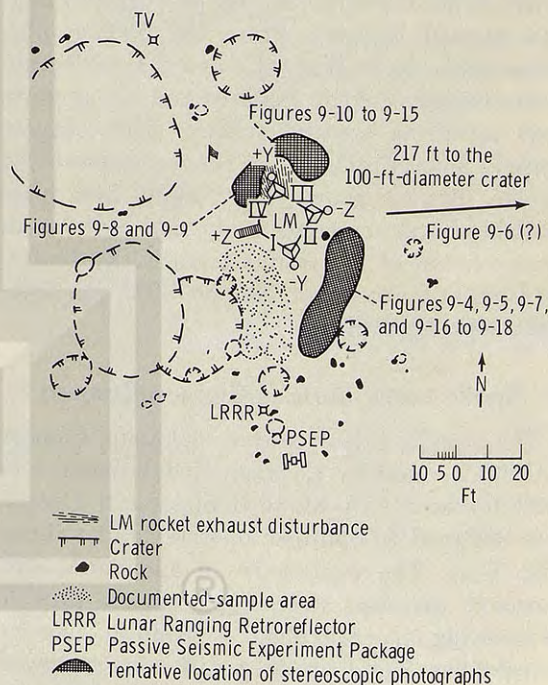


FIGURE 9-3. — Locations of ALSCC photographs.

FIGURE 9-4. — A small lump of lunar surface powder approximately 0.5 in. across, with a splash of glassy material over it. A drop of molten material appears to have fallen on the powder, splashed, and frozen.

FIGURE 9-5. — Clump of lunar surface powder with various small, differently colored pieces. Many small, shiny spherical particles can be seen.

FIGURE 9-5. — Clump of lunar surface powder with various small, differently colored pieces. Many small, shiny spherical particles can be seen.



FIGURE 9-4. — A small lump of lunar soil with a glazed top and a smaller glazed piece to the right. The larger object shows no change of color or texture compared with the surrounding ground, known to be soft, fine-grained soil, except for the glaze mark. (NASA AS11-45-6704)



FIGURE 9-6. — Stone embedded in powdery lunar surface material. (NASA AS11-45-6712)

Another stereoscopic view (fig. 9-6) shows a stone, approximately 2.5 in. long, embedded in the powdery lunar surface material. The small pieces grouped closely around the stone suggest that it suffered some erosion. On the surface, several small pits are seen, mostly less than one-eighth in. in size and with a glazed surface. The pits have a raised rim, characteristic of pits

made by high-velocity micrometeorite impacts.

One stereoscopic view (fig. 9-7) of the surface of a lunar rock shows an embedded $\frac{3}{4}$ -in. fragment of a different color. On the surface, several small pits are seen, mostly less than one-eighth in. in size and with a glazed surface. The pits have a raised rim, characteristic of pits made by high-velocity micrometeorite impacts.



FIGURE 9-5. — Clump of lunar surface powder (NASA AS11-45-6706)



FIGURE 9-7. — Stereoscopic view (NASA AS11-45-6709)

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The stereoscopic views in figures 9-8 to 9-20 are included in this report to make the availability of the photographs known. Descriptions or interpretation of these photographs were not available for this publication.

These photographs are available upon request from the NASA Manned Spacecraft Center, Houston, Tex. The following is a listing of the 17 photograph numbers, keyed to the figure number used in this chapter.

Figure	Photograph
9-4	AS11-45-6704
9-5	AS11-45-6706
9-6	AS11-45-6712
9-7	AS11-45-6709
9-8	AS11-45-6697
9-9	AS11-45-6698
9-10	AS11-45-6699
9-11	AS11-45-6700
9-12	AS11-45-6701
9-13	AS11-45-6702
9-14	AS11-45-6702-1
9-15	AS11-45-6703
9-16	AS11-45-6705
9-17	AS11-45-6707
9-18	AS11-45-6708
9-19	AS11-45-6710
9-20	AS11-45-6713



FIGURE 9-8. — Stereoscopic view (NASA AS11-45-6697)



FIGURE 9-9. — Stereoscopic view (NASA AS11-45-6698)



FIGURE 9-10. — Stereoscopic view (NASA AS11-45-6699)



FIGURE 9-11. — This is the affected area is close to (and presumably beyond) very regular fashion, with face upwards and out in consistently affected. The required to observe the di 45-6700)



FIGURE 9-12. — Stereoscopic



FIGURE 9-11. — This is the bottom of a crater, and the affected area is close to the upper edge of the frame (and presumably beyond). Here, glazing is seen in a very regular fashion, with the edges and points that face upwards and out in a direction to the upper right consistently affected. The stereoscopic view is required to observe the directional effect. (NASA AS11-45-6698)



FIGURE 9-13. — Stereoscopic view (NASA AS11-45-6702)



FIGURE 9-12. — Stereoscopic view (NASA AS11-45-6701)



FIGURE 9-14. — Stereoscopic view (NASA AS11-45-6702-1)



FIGURE 9-15. — Stereoscopic view (NASA AS11-45-6703)



FIGURE 9-17. — Stereoscopic view (NASA AS11-45-6707)



FIGURE 9-16. — Stereoscopic view (NASA AS11-45-6705)



FIGURE 9-18. — A large area of glazing is seen in the lower left region, both on the horizontal and on the sloping surfaces of the protuberance. Some glazing is also seen on the lower right object, with edges and points particularly affected. In the upper part of the picture a small glossy bead is seen poised on a narrow pedestal. (The detail in the color stereoscopic transparencies far exceeds that which can be reproduced in the present print.) (NASA AS11-45-6708)



FIGURE 9-19. — Stereoscopic view (NASA AS11-45-6709)



FIGURE 9-20. — Stereoscopic view (NASA AS11-45-6710)

Apollo 11 Observations of Glazing Phenomena

The Apollo 11 mission was the first time a man has walked on the Moon. The camera with which the photographs were taken has a resolution of approximately 100 lines per inch. Many details seen in

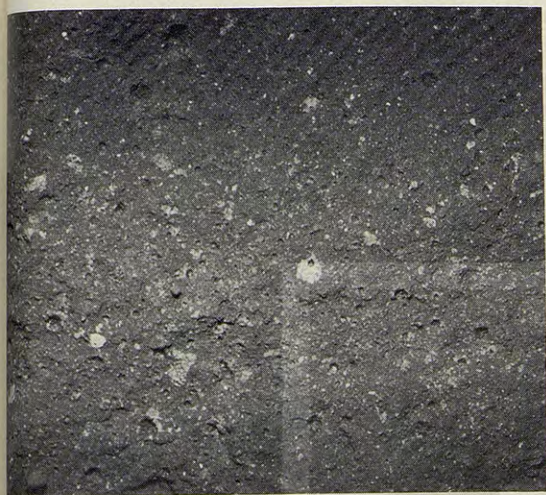


FIGURE 9-19. — Stereoscopic view (NASA AS11-45-6710)



FIGURE 9-20. — Stereoscopic view (NASA AS11-45-6713)

Apollo 11 Observations of a Remarkable Glazing Phenomenon on the Lunar Surface

T. Gold

The Apollo 11 mission carried a closeup stereo camera with which the astronauts took 17 pictures. Each is of an area 3 by 3 in., seen with a resolution of approximately 80 μ m. There are many details seen in these pictures that were not

known previously or that could not be seen with similar definition by Astronauts Armstrong and Aldrin in their careful inspection of the lunar surface. One of those is outstanding in being wholly unexpected and possibly of consequence not only to lunar geology but also to aspects of the study of the Sun, the Earth, and other bodies of the solar system.

The observation is that of glossy surfaces, in appearance a glass of color similar to the surrounding powdery medium, lying in very particular positions. Small craters that are plentiful on the lunar surface—6 in. to 2 or 3 feet in diameter—have frequently some clumps of the lunar soil or rough spots of the surface texture concentrated toward their center. They give the appearance of having been swept in at a time later than the formation of the crater. Some of these little lumps appear to have just their top surfaces glazed. The glassy patches that can be seen on the photographs range in size from $\frac{1}{2}$ mm to about 1 cm.

The glazed areas are clearly concentrated toward the top surfaces of protuberances, although they exist also on some sides. Points and edges appear to be strongly favored for the glazing process. In some cases, droplets appear to have run down an inclined surface for a few millimeters and congealed there.

The astronauts' information was that similar things were seen in many small craters, many more than the eight instances of which we have photographs. They were not able at the time to pick up any of the objects for the sample return. They did not see a single glazed piece in any different geometrical position other than near the center of a small crater. They were not able to handle any of the objects, and thus have no direct observation as to the thickness of the glass. Since they only saw them from eye-height, looking down at the ground in front of them, their visual acuity would be considerably less than that of the camera, and they could therefore not supplement the detailed information contained in the pictures.

Several theories of the origin of this phenomenon have to be discussed.

1. An effect connected with the rocket exhaust of the descent stage.

It might be thought that in the last phases of the landing process the rocket flame melted some lunar material and that this was blasted over the surrounding terrain. While at first this seems a very attractive hypothesis, when pursued in more detail it runs into difficulties. These are concerned with the regional distribution of the objects and also with the detailed geometrical relationships in the places where they are seen.

The astronauts noticed these objects first in a region ahead and to one side of the landing approach path, about 50 ft from the spacecraft. The pattern of disturbance caused by the rocket could be seen to extend hardly beyond the footpads of the spacecraft. The inspection of the approach path and the region directly underneath the nozzle of the rocket showed the ground disturbed there, but no evidence of any melting was seen. It seems most unlikely that if melting occurred, all molten material was blasted away, not leaving a higher concentration near the source.

No explanation can be found of how material so flung out would end up concentrated in little clumpings in the bottoms of small craters without there being also some on the flat surface or in much shallower depressions. The material could not be thought to have been propelled by gas drag and to have slid over the surface, to land perhaps in sheltered holes, since the rocket gas-drag forces are quite inadequate at a distance of more than a few feet from the rocket. This is substantiated by the fact that the radially streaked pattern of the ground radiating out from underneath the spacecraft disappears at a distance of between 10 and 15 ft. No glassy objects could have been dragged over the surface by this stream at a distance of 50 ft; if they had been flung that far, they would be lying essentially where they landed, and no reason is then seen for the specific distribution that was found.

The glassy objects were, by the astronauts' descriptions, substantiated by the pictures, usually found in a tight clumping, and the pictures indicate in several cases a definite common azimuth dependence of the effect among the members of any one group. (There is no record of the azimuth position of the camera, so different groups cannot be compared with

each other; but the camera was generally held facing nearly vertically downward. The astronauts were not aware of any azimuth effect, nor could they have been expected to see it, since it becomes evident only from a careful study of the high-resolution pictures.)

It thus seems extremely improbable that any effect of the rocket exhaust can be held responsible for the phenomenon.

2. Splashing of liquid drops from a larger impact elsewhere.

Many of the same objections can be raised again here. Such droplets could not have landed in preferential places. On impact, with the velocities necessary from a source more than a few feet away, they would have toppled and destroyed many of the frail structures that they hit, and thus the geometrical relationships would have been lost.

3. The objects are common in the ground, where they were distributed after being created by shock heating or volcanism. Erosion has exposed some of them.

The fact that the objects are found in the bottoms of little craters argues against slow erosion exposing them, for these craters are filled up and not emptied out by the lunar surface transportation processes. There are many cases of a clearly visible outline of the glazing, showing shapes characteristic of viscous flow defining that outline. One is clearly not dealing with entirely glazed objects of which only a certain fraction is cleaned off and exposed, but rather one is dealing with objects that are covered with a glaze mainly on top.

Small glassy spheres had been reported to be common in the lunar soil, and many are indeed also seen on the pictures. Their origin may be understood merely as a consequence of meteoritic impact melting and freezing during the ballistic trajectory of the ejected material. If the ground has been plowed over many times by impacts, as suggested by the topography of the Moon, a substantial admixture of spheres and other shapes resulting from only partial melting must indeed be expected in the ground. The glazed surfaces discussed here appear not to be of this character. Fragments of them may also appear in the lunar soil, and those would be expected

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4. They are objects created by the impact that made the little craters in which they are now found.

This seems impossible in view of the fact that they are frequently quite frail structures, apparently only made of the powdery material, and they could not have survived and remained there in definite geometrical positions when an explosive force excavated the crater. While in a hard rock a glazed coating may remain lining the impact pit, this is very unlikely in a soft soil. All material exposed to enough heat to melt would be exposed also to aerodynamic forces large enough to be expelled. Any glass made by a strong pressure wave in the ground and subsequently exposed would not have glossy surfaces except as a result of fracture. The shapes seen are in most cases clearly the result of a surface viscous flow and not of a fracture.

5. Radiation heating.

An intense source of radiative heating could account for all the facts that are now known. The wavelength of this radiation could be anywhere in the electromagnetic spectrum between the far ultraviolet and the far infrared. For radiative heating from a small angular source in the sky the bottoms of craters are substantially favored. The equilibrium temperature in a given radiation field is likely to be between 10 and 20 percent in absolute temperature above that of flat ground. (This problem has been discussed in some detail by Buhl, Welch, and Rea (ref. 9-1).) The reason for that is, of course, the diminution of the solid angle subtended by the cold sky for a particle in a hollow compared with one on flat ground. There is thus an intensity range where radiation heating will cause melting only in the bottoms of craters. The positioning of the objects can be understood in these terms.

No significant mechanical forces would be involved, and frail structures could suffer melting of their upper surface without being deranged. One protuberance, for example, shows no change in color or texture from the surrounding medium known to be soft powder; yet it has a large patch of glazed material over the top of it. If the source of the heating were not directly

overhead, there could be a common azimuthal preference for the melted surfaces.

Protuberances, rather than flat ground, and sharp points and edges would be favored for melting if the heat source existed for a short time only. The reason for this is that heat conduction will carry less heat away from such positions, and they would reach the temperature corresponding to the local radiative equilibrium sooner than would flat surfaces. The observations are very clear in demonstrating such an effect. Similarly, the apparently thin coating of glaze clearly seen in many of the pictures indicates a short duration for the period of the radiative heating. With the approximately known rate of heat transfer in the lunar material, one may estimate that the duration of the heating phase was between 10 and 100 sec.

Among the interpretations discussed here, only radiative heating seems to be able to account for the major observational data; and it accounts well for both the distribution over the ground and the detailed geometrical arrangements in which the glazing is found, for it is in just those places that the temperature would be expected to be at a maximum. We must therefore seek clues as to the nature of such a flash of radiation.

The time of occurrence of the flash heating would have to have been sufficiently recent for micrometeorites not to have destroyed the glaze, nor for the mechanisms that redistribute the lunar soil to have blanketed the objects. Estimates of the micrometeorite rate at the present time vary considerably, but it seems very unlikely that the glaze could be maintained on the surface for as much as 100 000 yr and probably not for more than 30 000. The event in question would thus have to have taken place within this geologically very recent past. Several possibilities have to be discussed.

a. An impact fireball on the Moon.

A large impact would no doubt generate intense radiation from the explosive gas cloud. This radiation will, however, be largely screened from reaching areas outside the crater made by the impact, and it seems unlikely that high radiation intensities would extend over regions beyond those swept over by the explosive action

or the expelled material. Craters would be particularly unfavorable locations for such a source of heat, rather than highly favored as the observations show.

b. An impact fireball on the Earth.

Although very large impacts may have taken place on the Earth within geologic time, and may indeed be responsible for some of the widespread falls of tektites, no really major event is thought to have occurred within the sufficiently recent past. The energy released in an impact on the Earth of a 1-km meteorite at a velocity of 20 km/sec is of the order of 3×10^{27} ergs and that, if it were all converted into radiation, would deposit on the order of 4×10^5 ergs/cm² on the lunar surface. The value required to cause the observed effect is of the order of 3×10^9 ergs/cm². No fireball of adequate intensity seems to have existed on the Earth within the last hundred thousand years.

c. A flash from the Sun.

One can calculate the increase in the solar emission that would be required to cause melting in favorable places on the lunar surface. The normal noontime temperature on the lunar equator is known to be approximately 394° K. The analysis of Buhl et al. (ref. 9-1) shows that the absolute temperature in the bottom of a hemispherical crater must be expected to rise about 11 percent above that of the surrounds. The normal noontime temperature would thus be 437° K in such locations. If f is the factor by which the solar luminosity is increased, we require that

$$f = \left(\frac{T_m}{T_0} \right)^4$$

where T_m is the melting temperature and T_0 the normal temperature in the same location. If we adopt a melting temperature of the lunar surface material of 1400° K, an appropriate figure for basalt, the value of f would be 106. The temperature of the flat ground in the same radiation field would then be 1260° K. (For a brief flash the fact that a crater bottom started out 40° hotter would further increase the margin between melting there and elsewhere.)

The flash heating, if it originated from the Sun, overhead at the time in the lunar region in question, thus requires that the Sun's luminosity

flared up for a period of between 10 and 100 sec to a luminosity of more than 100 times its present value. What could be the origin of such a flareup?

Solar flares, as they are known at the present time, only reach a total energy output of less than 10^{33} ergs. The quantity we are discussing here is at least 4×10^{36} ergs for an isotropic source, or 2×10^{36} ergs for a localized source on the Sun that radiates into a hemisphere only. While it cannot be ruled out completely that flares of such an intensity could occur, we have no evidence in this regard, although some earlier speculations exist (ref. 9-2).

The phenomenon may not be in the nature of a flare, but in the nature of a very minor novalike outburst of the Sun. The nova phenomenon among the stars is not understood, but it is normally concerned with a different class of star, and the intensity of the outburst, up to 100 times the normal luminosity, for a period of only tens of seconds every few tens of thousands of years, would be a phenomenon that would not have been recognized astronomically among stars of the solar type. One can therefore not completely rule out the possibility that stars like the Sun do have occasional instabilities of internal origin, but very much weaker than the novae.

The infall into the Sun of a comet or asteroid is another possibility.¹ An object falling into the Sun at the velocity of escape would have to have a mass of 3×10^{21} g for the kinetic energy to be sufficient to generate the flash. This would put the object into the class of asteroids or very large cometary cores.

For the infalling energy to be converted into radiation in its entirety, it would be necessary for the object to break up in the solar atmosphere, and for no substantial pieces to remain intact at the level of the photosphere. Tidal disruption and violent heating could perhaps be invoked to break up a cometary body more readily than an asteroidal one. Also, comets have been known to approach the Sun very closely in historical times, and the statistical evidence would be that many have hit the Sun in a period of 30 000 years. The mass required (3×10^{21} g) is above that which has been guessed at for presently known comets.

¹Suggested by F. Hoyle.

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²F. Whipp

³Suggested

An icy cometary core would have to have a radius of approximately 100 km, while some presently known comets² may have cores as large as 50 km. The suggestion that the flash was due to an infalling comet seems to merit further attention.

If such a flash occurred on the Sun within geologically recent times, there are many other consequences that may perhaps be recognized on the Earth or other planets. If the flash occurred as a result of an infalling object, or of a superflare, or of an internal outburst that exposed subphotospheric material, its spectrum would be mainly in the ultraviolet. So far as the Earth is concerned, the total extra heat delivered would be mainly spread in the atmosphere and does not cause a substantial rise in the temperature of the lower atmosphere. The heat delivered to the ground is not likely to have been enough to cause any permanent effects. Nevertheless, there may be effects in the geologic record that can be attributed to such an event. The upper atmosphere of the Earth and of Venus, and the entire atmosphere of Mars, would, however, have been seriously affected. On the Earth, the ratio of ³He and ⁴He in the outer atmosphere suggests that there is no substantial preferential loss by slow evaporation of ³He (refs. 9-3 and 9-4). If the outer atmosphere were entirely swept away by such outbursts, then the present ratio, which implies an absence of a preferential thermal evaporation at normal temperatures of ³He, would be more readily understood. The apparent absence of nitrogen on Mars, as reported from the data of the Mariner 6 and 7 flights, could also be understood if the entire atmosphere had been swept away and, in the short time since, had been replenished only from the constituents frozen out on the polar cap, which may be CO₂, but not nitrogen.³

²F. Whipple, private communication.

³Suggested by C. Sagan.

Flash heating on the surface of Mercury would have been much more intense, and if made of lunar-type rock, almost an entire hemisphere would have been glazed. We do not know the surface material, nor the effects of erosion and solar irradiation on Mercury, and the absence now of a glazed hemisphere could be understood as due to a different material or a faster destruction of glass on Mercury than on the Moon.

No doubt many more facts will come to light concerning the lunar surface and, perhaps, this phenomenon, in the analysis of the lunar samples brought back by Apollo 11. A rapid publication of these findings was nevertheless indicated by the urgency to make the best possible scientific preparations for the next Apollo flights.

A more complete review of this and other information contained in the closeup pictures will be published later.

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ACKNOWLEDGMENTS

I am indebted to the National Aeronautics and Space Administration for arranging for the construction and deployment of the closeup camera; to E. Purcell, E. Land, J. Baker, R. Scott, and F. Pearce for their contributions in outlining this camera project; to Eastman Kodak for the design and fabrication of the instrument; and chiefly to N. Armstrong for his successful use of it, and his excellent descriptions of all relevant lunar surface observations made by himself and E. Aldrin. Work on the lunar closeup camera and the analysis of photographs obtained with it is supported at Cornell under NASA Contract Number NAS9-9017. I am grateful to F. Hoyle, F. L. Whipple, G. J. F. MacDonald, and S. Soter for helpful discussions.

10. The Modified Dust Detector in the Early Apollo Scientific Experiments Package

J. R. Bates, S. C. Freden, and B. J. O'Brien

The modified dust detector (fig. 10-1) in the Early Apollo Scientific Experiments Package (EASEP) consists of three n-on-p silicon solar cells mounted on the top horizontal surface of the dust-detector housing. The objectives of the dust-detector experiment, which is also referred to as the Dust, Thermal, and Radiation Engineering Measurements Package (DTREM I), are to measure dust accumulation resulting from the LM ascent or from any long-term cause and to measure radiation degradation of the voltage output from the solar cells. The radiation degradation is caused by solar-flare particle events.

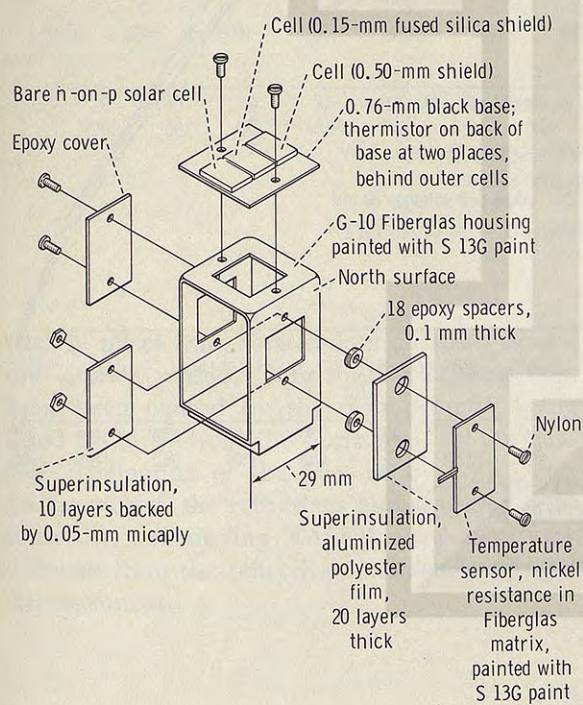


FIGURE 10-1. — Dust, Thermal, and Radiation Engineering Measurement Package (modified dust-detector experiment) on the Apollo 11 EASEP.

The concept of radiation measurement by a dust detector is fairly straightforward. Radiation degradation of the voltage output from a solar cell is predictable. If a glass shield is placed over the surface of a solar cell, particles above certain energies will damage the cell. The particle energy required to damage the cells is determined by the thickness of the glass shield.

A preliminary analysis of data received in the Mission Control Center (MCC) on the first lunar day that the experiment was operational showed no appreciable cell degradation caused by dust or debris from the LM ascent. Shadows from the antenna, the antenna alining pole, and the carrying handle (fig. 10-2) were evident on the dust-detector outputs from day 205.5 to day 208 (figs. 10-3 and 10-4).

In the preliminary analysis, the voltage outputs from the solar cells on the dust detector were 10 percent less at lunar noon than pre-launch predictions had indicated. These lower-than-predicted voltage outputs may have been caused by dust, but they may also have been a result of errors in the prelaunch calibration measurements of the cells and errors in the calibration data used in the MCC. Figures 10-3 and 10-4 are samples of the real-time data received in the MCC.

The maximum temperature of the solar cells on the dust detector during the first lunar day of the experiment was approximately 104° C. However, this temperature was recorded after lunar noon, and shadowing of the dust detector (from the antenna, the antenna alining pole, and the carrying handle) occurred just before lunar noon. Without shadowing, the temperature might have been 5° to 10° C higher.

The dust-detector data obtained during the sunset period of the lunar day appear to be

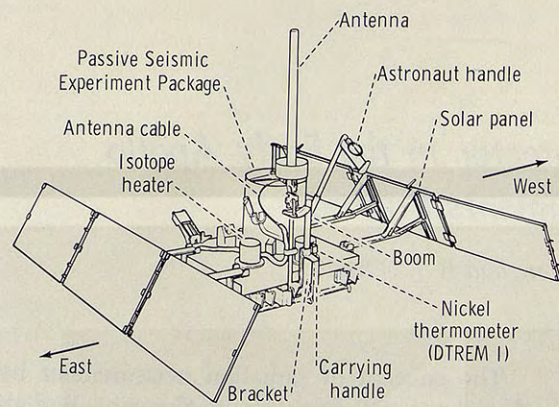


FIGURE 10-2. — Deployed configuration of the Passive Seismic Experiment Package showing the geometry of the DTREM I.

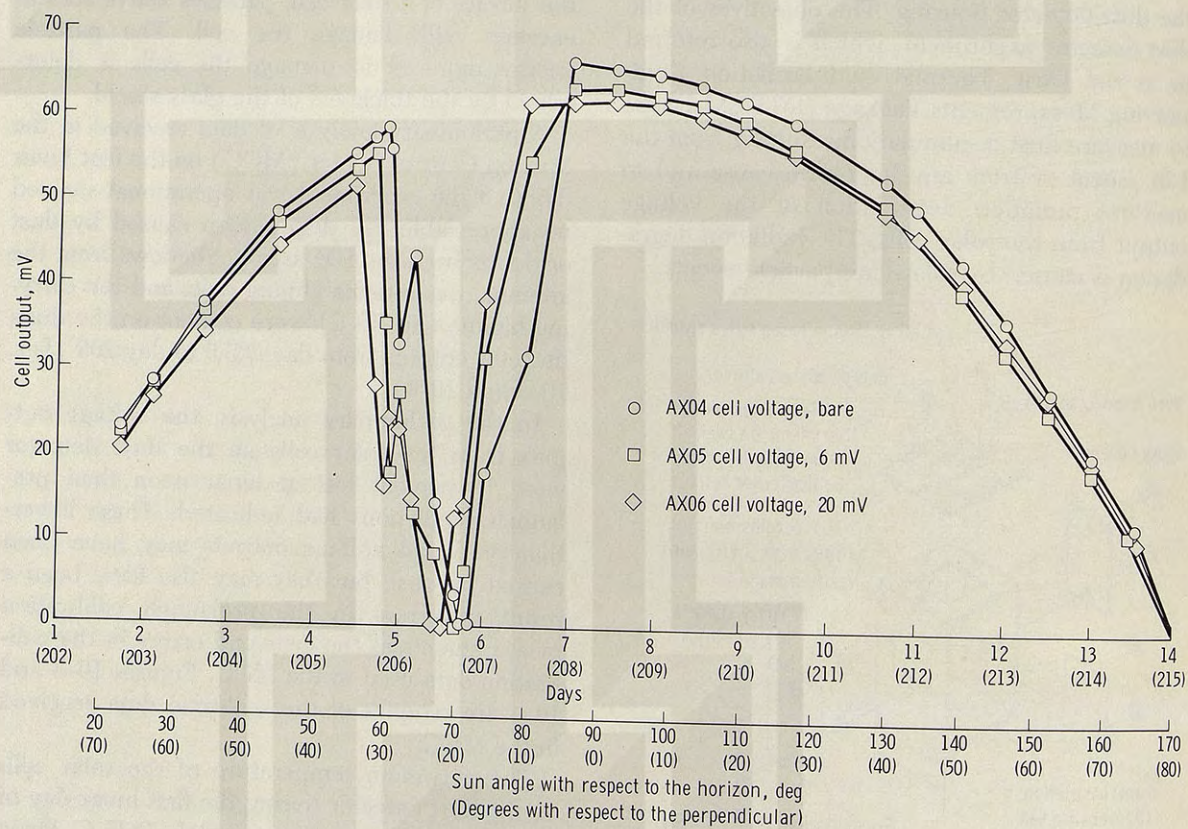
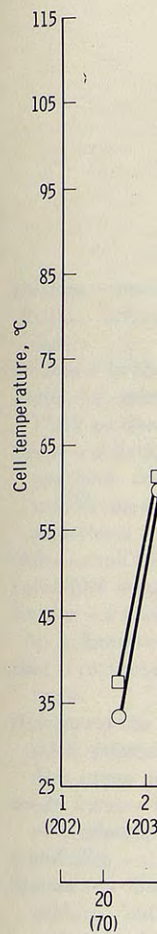


FIGURE 10-3. — Dust-detector solar-cell output.



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from the sun
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during sunrise

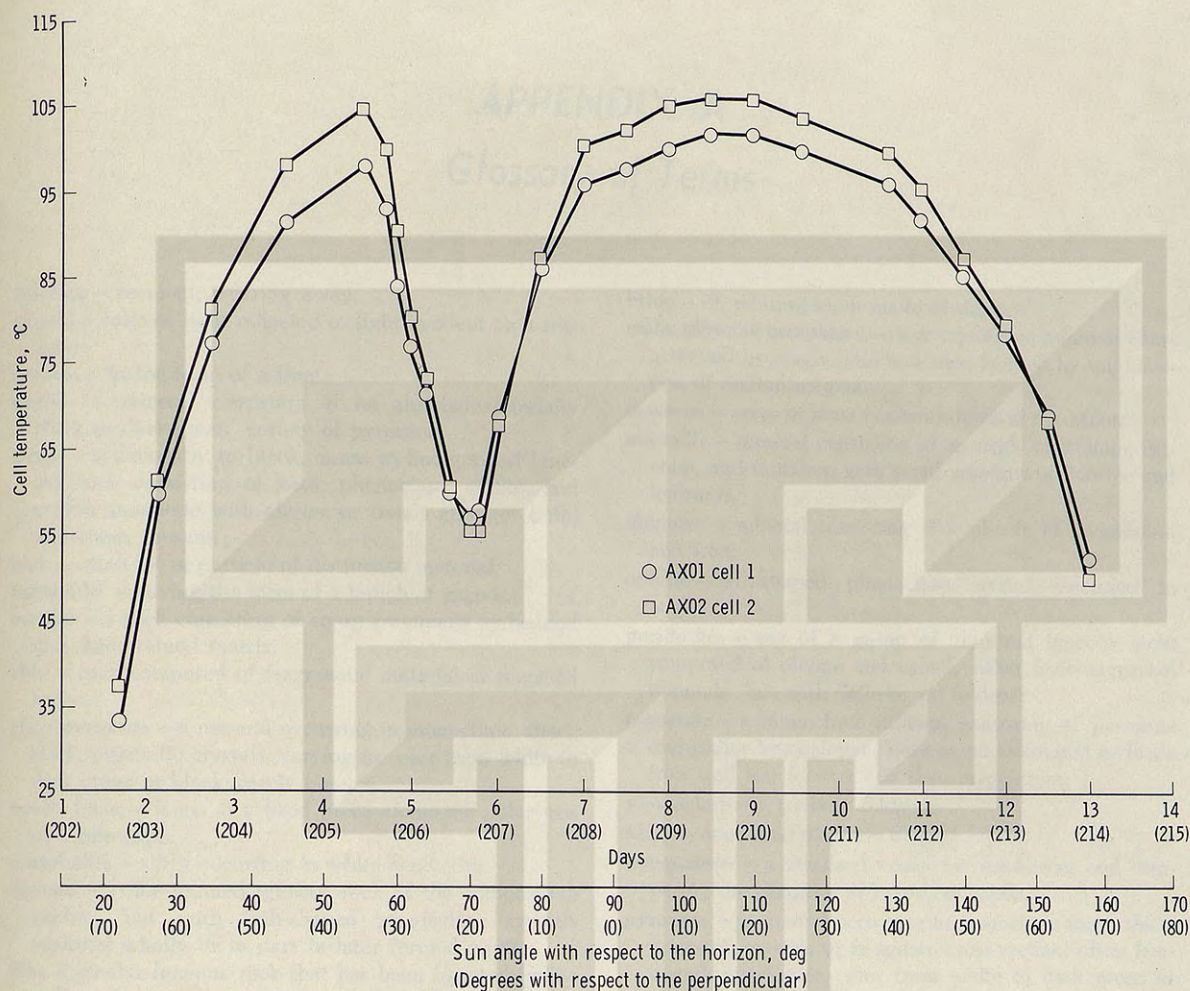


FIGURE 10-4. — Dust-detector solar-cell temperature.

slightly offset from similar data obtained during the sunrise period. This slight offsetting may have been caused by the dust detector being tilted 2° to 5° from the horizontal, by the non-zero declination of the Sun, or by both. Also, during sunset, the reflections and scattered light from the surrounding EASEP components are different from the reflections and scattered light during sunrise.

To detect degradation of the solar cells, data obtained on the first lunar day of the experiment will be compared with data obtained on successive lunar days. After sufficient data have been accumulated, a detailed analysis and establishment of baseline conditions will be made by using off-line computer routines that contain exact calibration data.

APPENDIX A

Glossary of Terms

- ablation** — removal; wearing away.
- albedo** — ratio of light reflected to light incident on a surface.
- arcuate** — in the form of a bow.
- augite** — a mineral consisting of an aluminous, usually black or dark-green, variety of pyroxene.
- basalt** — a dark-gray to black, dense to fine-grained igneous rock consisting of basic plagioclase, augite, and usually magnetic with olivine or basalt glass (or both) sometimes present.
- bleb** — small bit or particle of distinctive material.
- botryoidal** — having the form of a bunch of grapes.
- breccia** — a rock consisting of sharp fragments embedded in a fine-grained matrix.
- clast** — rock composed of fragmental material of specified types.
- clino-pyroxene** — a mineral occurring in monoclinic, short, thick, prismatic crystals, varying in color from white to dark green or black (rarely blue).
- coudé focus** — focus at a fixed place along the polar axis of a telescope.
- cristobalite** — silica occurring in white octahedra.
- diabase** — a fine-grained igneous rock of the composition gabbro, but with lath-shaped plagioclase crystals enclosed wholly or in part in later formed augite.
- dike** — tabular igneous rock that has been injected (while molten) into a fissure.
- diktytaxitic** — volcanic rock of clastic appearance.
- equant** — having crystals with equal or nearly equal diameters in all directions.
- ehedral** — refers to minerals whose crystals have had no interference in growth.
- exfoliation** — the process of breaking loose thin concentric shells or flakes from a rock surface.
- feldspathic** — pertaining to feldspar.
- finer** — very small particles in a mixture of various sizes.
- gabbro** — a granular igneous rock composed essentially of calcic plagioclase, a ferromagnesian mineral, and accessory minerals.
- hackly** — rough; jagged; broken.
- holocrystalline** — consisting entirely of crystals.
- ilmenite** — a usually massive, iron-black mineral of sub-metallic luster.
- induration** — hardening.
- Kapton** — insulating material used in the construction of the lunar module.
- lithic** — of, relating to, or made of stone.
- mafic plutonic complexes** — dark crystalline minerals characterized by magnesium and iron; formed by solidification of molten magma.
- mascons** — areas of mass concentrations of the Moon.
- microlite** — mineral consisting of an oxide of sodium, calcium, and tantalum with small amounts of fluorine and hydroxyl.
- olivine** — a mineral consisting of a silicate of magnesium and iron.
- ophitic** — lath-shaped plagioclase crystals enclosed in augite.
- peridotites** — any of a group of granitoid igneous rocks composed of olivine and usually other ferromagnesian minerals, but with little or no feldspar.
- pigeonite** — a monoclinic mineral consisting of pyroxene and rather low calcium, little or no aluminum or ferric iron, and less ferrous iron than magnesium.
- plagioclase** — a triclinic feldspar.
- platy** — consisting of plates or flaky layers.
- pycnometer** — a standard vessel for measuring and comparing the densities of liquids or solids.
- pyroxene** — a mineral occurring in monoclinic short, thick, prismatic crystals or in square cross section; often laminated, varying in color from white to dark green or black (rarely blue).
- pyroxenite** — an igneous rock that contains no olivine and is composed essentially of pyroxene.
- regolith** — the layer of fragmental debris that overlies consolidated bedrock.
- shards** — angular curved fragments.
- subhedral** — incompletely bounded by crystal planes.
- terra** — an area on the lunar surface that is relatively higher in elevation and lighter in color than the maria. The terra is characterized by a rough texture formed by intersecting or overlapping large craters.
- traverse map** — a map made from a series of movements that are joined end to end and are completely determined as to length and azimuth.
- troilite** — a mineral that is native ferrous sulfide.
- twinned** — refers to two craters with overlapping rims.
- vesicle** — a small cavity in a mineral or rock ordinarily produced by expansion of vapor in the molten mass.
- vug** — a small cavity in a rock.

APPENDIX B

Acronyms

ALSCC — Apollo Lunar Surface Closeup Camera	MCC — Mission Control Center
ALSEP — Apollo Lunar Surface Experiments Package	MESA — Modularized Equipment Storage Assembly
ALSRC — Apollo Lunar Sample Return Container	MIT — Massachusetts Institute of Technology
BRN — Brown & Root-Northrop	MQF — Mobile Quarantine Facility
CAPCOM — capsule communicator	MSC — Manned Spacecraft Center
CM — command module	MSTPHC — multistop time-to-pulse height converter
CRA — Crew Reception Area	NASA — National Aeronautics and Space Administration
CSM — command and service module	ORNL — Oak Ridge National Laboratory
DPS — descent propulsion system	PET — Preliminary Examination Team
DTREM I — Dust, Thermal, and Radiation Engineering Measurements Package	PLSS — portable life support system
EASEP — Early Apollo Scientific Experiments Package	PSEP — Passive Seismic Experiments Package
e.d.t. — eastern daylight time	RCL — Radiation Counting Laboratory
EVA — extravehicular activity	SL — Sample Laboratory
g.e.t. — ground elapsed time	SM — service module
JPL — Jet Propulsion Laboratory	SP — short period
KSC — Kennedy Space Center	SRC — sample return container
LEC — Lunar Equipment Conveyor	STP — standard temperature and pressure
LM — lunar module	SWC — Solar-Wind Composition
LP — long period	TDG — time-delay generator
LPZ — vertical-component seismometer	TIM — time-interval meter
LRL — Lunar Receiving Laboratory	TV — television
LRRR — Laser Ranging Retroreflector	USGS — U.S. Geological Survey
	u.t. — universal time

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