# 6. *Passive Seismic Experiment*

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## Purpose of the Passive Seismic Experiment

The Passive Seismic Experiment Package (PSEP), which was deployed on the lunar surface by the Apollo 11 astronauts, was the principal tool for determining the internal structure, physical state, tectonic activity, and composition of the Moon. Detailed investigation of the lunar structure must await the establishment and operation of a network of seismic stations; however, a single suitable well-recorded seismic event can provide information that is of fundamental importance and that could not be gained in any other way.

The PSEP flown on the Apollo 11 mission offered the first opportunity for demonstrating the feasibility of lunar seismic exploration. Seismometers are among the most delicate of scientific instruments. They are normally operated on piers in underground vaults at sites especially selected for environmental stability and a low level of background noise. The impossibility of attaining such favorable operating conditions on the lunar surface posed many design problems. A principal goal of this experiment was to demonstrate the feasibility of obtaining seismic records of motions of the lunar surface and to interpret them in terms of lunar structure. The problem to be resolved was to produce seismometers that could be installed with a minimum demand on an astronaut's time and energy, be adjusted and calibrated by remote control, be operated on a foundation with uncertain mechanical properties and with sensitivity characteristics that could be adjusted to conform with the background noise characteristics of the Moon, and that could remain operable through the large changes in temperature on the lunar surface.

The PSEP was successfully installed at Tranquility Base as part of the Apollo 11 mission and was operated for 21 days. It demonstrated that the goals of lunar seismic exploration could indeed be achieved.

## Instrument Performance

The PSEP is shown schematically in figure 6–1. The system weighs 48 kg and uses solar cells to supply power. Thus, operation of the PSEP is confined to lunar day. The PSEP sensor unit contains three long-period (LP) seismometers with resonant periods of 15 sec, alined orthogonally to measure surface motion in both horizontal and vertical directions, and a single-axis, short-period (SP) seismometer sensitive to vertical motion at higher frequencies (resonant period of 1 sec).

Low-frequency, horizontal-component seismometers are extremely sensitive to tilt and must be leveled to high accuracy. In the Apollo seismic system, the two low-frequency, horizontal-component seismometers are leveled to within 2 seconds of arc from the local vertical direction by means of a two-axis, motor-driven gimbal (one motor for each seismometer). A third motor adjusts the low-frequency, vertical-component seismometer in the vertical direction. Motor operation is controlled from the Earth. These elements are shown schematically in figure 6–2. The low-frequency seismometers are mounted in crisscross fashion to achieve a minimum volume configuration. The instrument is controlled from the Earth by a set of 15 commands that control such functions as speed and direction of the leveling motors, instrument gain, and calibration.

Seismic data were obtained from the Apollo 11 seismometer system for 21 days. Initial activa-

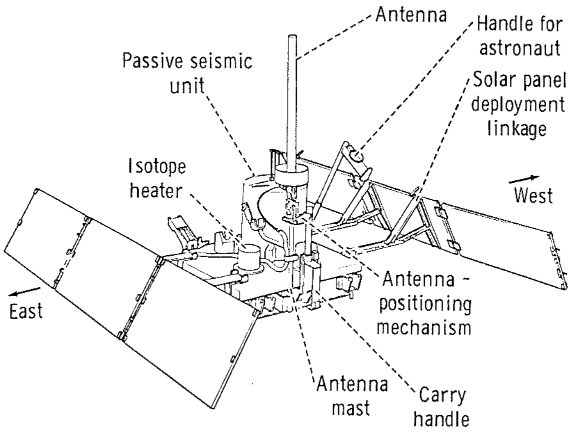

FIGURE 6-1. — Diagram of the fully erected PSEP.

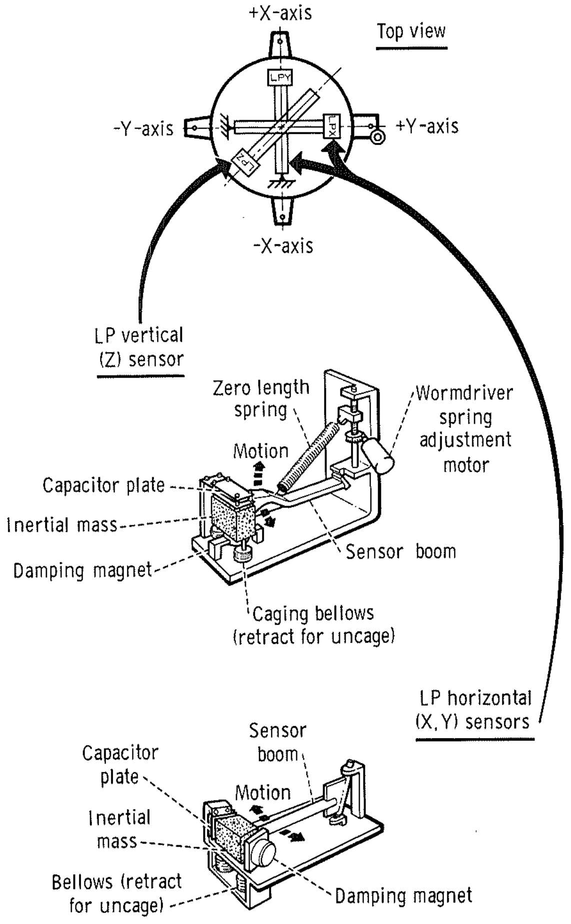

FIGURE 6-2. — Schematic diagrams of the elements of the low-frequency (LP) seismometers.

tion was on July 21, 1969, and final turnoff was on August 27, 1969. The instrument was emplaced south of the lunar module (LM), 16.8 m from the nearest point of the LM, as shown in figure 3–16. The PSEP is shown erected on the lunar surface in figure 6–3.

Termination of the experiment on August 27 resulted from failure of the system to receive and execute commands from Earth. Analysis of calibration pulses and signals received from various astronaut activities indicates that all four seismometers operated properly until the final 2 days of operation when the LP seismometers drifted out of their operating ranges and could not be recentered because of the absence of command capability. Instrument response curves, as derived from calibration pulses, are shown in figure 6–4.

Aside from the eventual failure of the system to respond to commands, the most significant deviation from nominal operating characteristics was that the actual maximum instrument temperature (190° F) exceeded the planned maximum (140° F) by 50° F. This resulted in occasional transient signals on the LP seismometer channels and several other minor effects, but did not significantly degrade instrument performance. The PSEP performance fully demonstrated the feasibility of operating seismic instruments in the lunar environment.

One problem that became evident in the early stages of the experiment was that the LM is a source of seismic signals of unexpectedly large amplitudes. Such seismic signals are assumed to be generated primarily by venting gases or circulating fluids, or both, within the LM. Inelastic deformation of the LM structure in response to thermoelastic stress may also be a significant source of seismic noise. Such noise signals make interpretation of the data obtained from the experiment more difficult because they must be recognized and separated from the signals of events of natural origin that are sought.

The problem of seismic noise from the LM will be reduced in later missions when the seismometers can be deployed at greater distances from the LM. Because of this problem, every effort must be made to achieve the greatest possible separation between the LM and the seismometers.

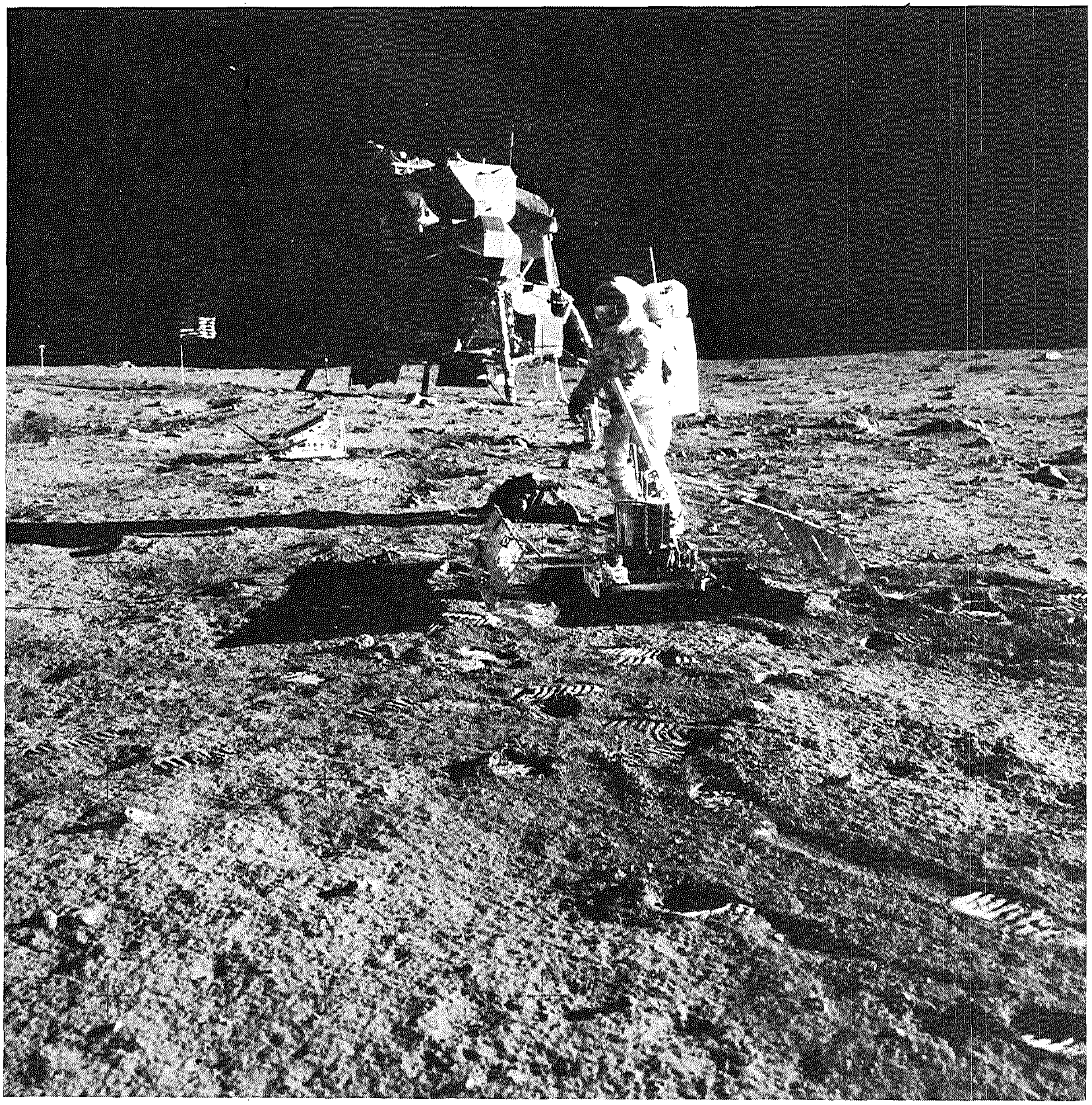

FIGURE 6-3. — Photograph of the PSEP immediately after its deployment on the lunar surface.

## Description of Recorded Seismic Signals

### *LP Seismometers*

Aside from occasional transient signals of instrument origin, the most conspicuous signals observed on the seismograms from the LP seismometers are a series of wave trains having the appearance of surface waves, that is, waves that would propagate along the surface of the Moon in contrast to body waves, which travel through the lunar interior. A total of 30 such signals can be clearly identified. No signals that might be classified as body waves are observed in relation to these wave trains. Most of the trains begin with SP (2 to 4 sec) oscillations that gradually increase to periods of 16 to 18 sec; that is, the

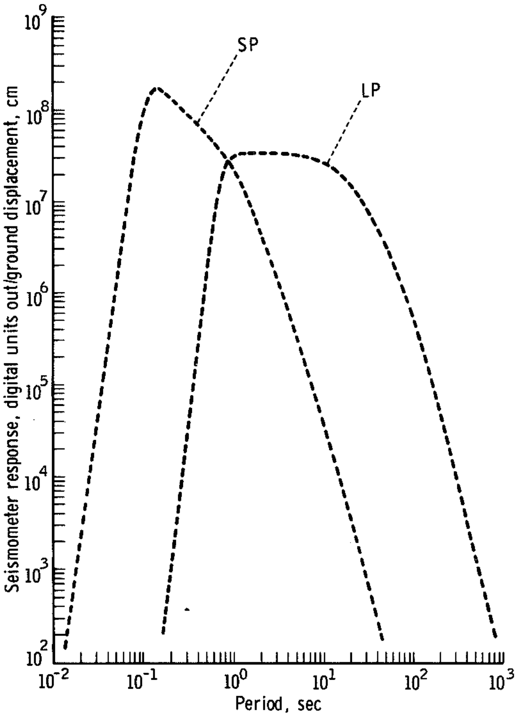

FIGURE 6-4. — Response curves for the SP and LP seismometers (for the highest gain setting). Response curves for the three LP seismometers are matched to within 5 percent. One digital unit is equal to 5 mV.

trains are dispersed. The first of these recorded wave trains is shown in figure 6-5. This wave train is primarily on the $x$-component. For several wave trains, the period range is between 20 and 50 sec. No corresponding signals are found on the LP vertical-component seismograms. Dispersion curves (wave period versus arrival time) for the first three wave trains are shown in figure 6-6.

During the second lunar day that the experiment was operational, several of these wave trains were observed to occur simultaneously with a series of pulses on the SP vertical seismometer. The pulses on the SP vertical seismometer are of uniform amplitude, and the time interval between pulses gradually increases. In the situations where wave trains and pulses on the SP vertical seismometer occur simultaneously, it is evident that the LP wave trains are simply the summation of the transient signals that correspond to the pulses. Amplitudes are of the order of 10 mμm peak-to-peak, so these are extremely small signals. While a natural origin for these signals cannot presently be excluded, the evidence strongly suggests that this entire set of signals is produced by instrumental effects that are, as yet, unexplained.

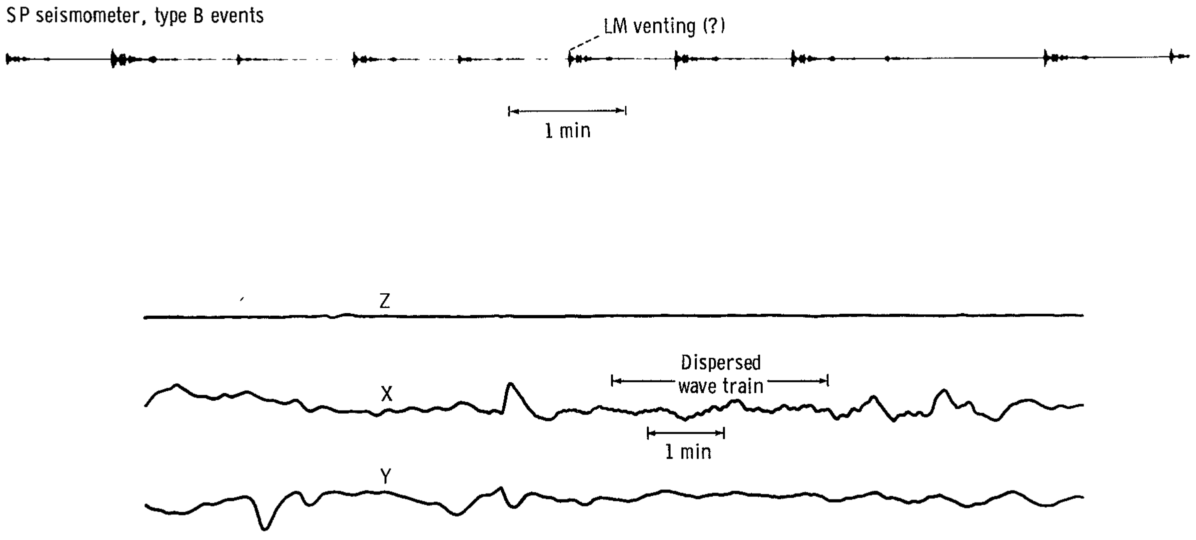

FIGURE 6-5. — Sample of a high-frequency seismic signal, perhaps generated by the LM, recorded by the SP seismometer and a sample of the background noise on the LP seismometer channels. This section of the seismic record includes one of the dispersed wave trains.

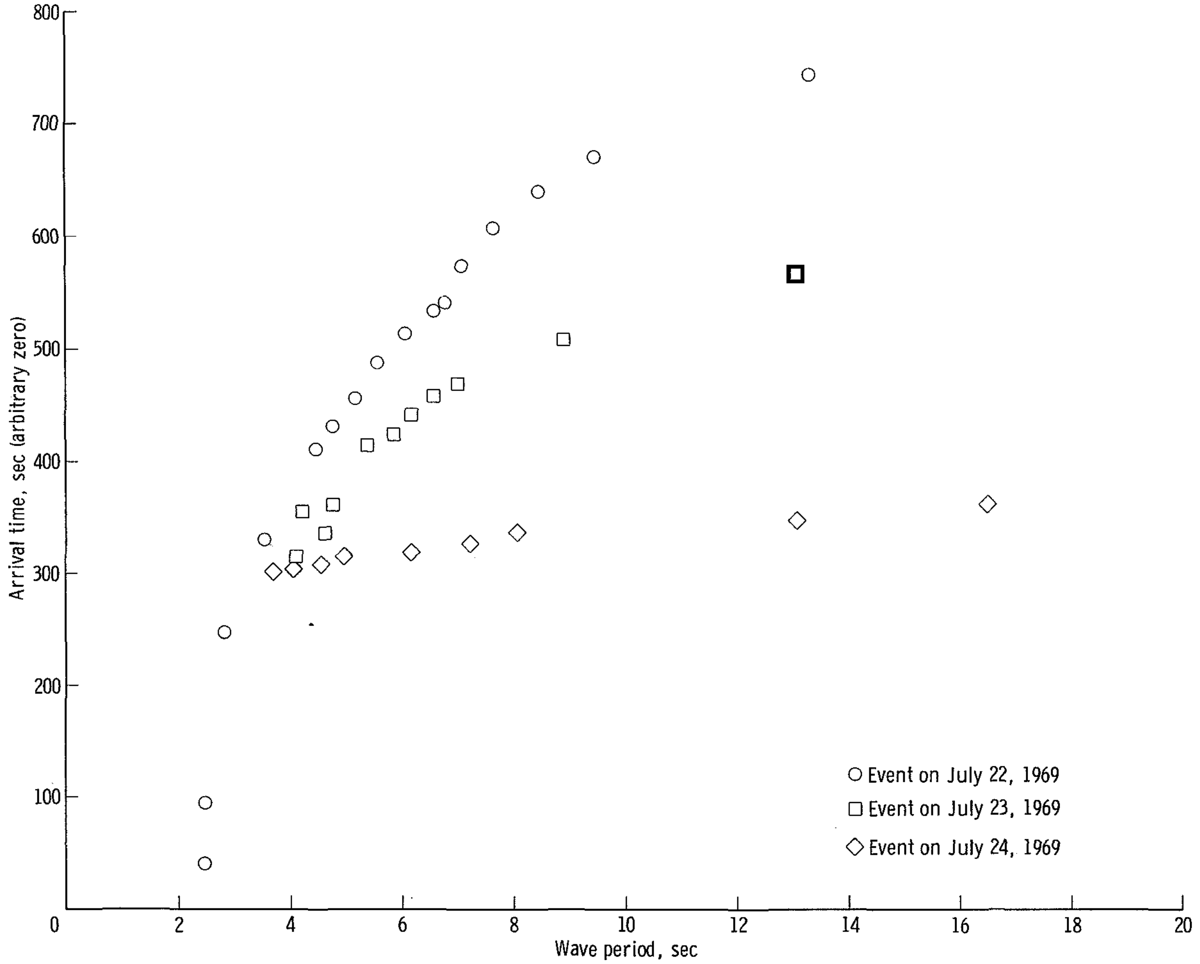

FIGURE 6-6. – Dispersion curves (wave train period versus arrival time) for three of the dispersed wave trains recorded by the SP seismometer.

### *The SP Seismometer*

A great variety of high-frequency (2 to 18 Hz) signals is present on the seismograms from the SP seismometer. As a part of the preliminary investigations, an attempt has been made to sort these signals into descriptive categories based primarily upon the shapes of the signal envelopes and the spectral characteristics of each type. Only a few spectra are available at the present time. The signals are divided into the following categories:

(1) Signals produced by astronaut activities while the astronauts were on the lunar surface (type A)

(2) Signals with impulsive onset and relatively short duration (types I and X)

(3) Signals with emergent onset and relatively long duration (types B, M, T, and L)

Refinement in this categorization process can be expected as the investigation proceeds. Such refinement will be conducted with a view toward a better understanding of the source mechanisms involved.

*Type A.* Signals produced by astronaut activities were prominent on the SP seismometer from initial operation until LM ascent. Such signals were particularly strong when the astronauts were in physical contact with the LM. The signal produced when Astronaut Neil A. Armstrong ascended the ladder to reenter the LM is shown

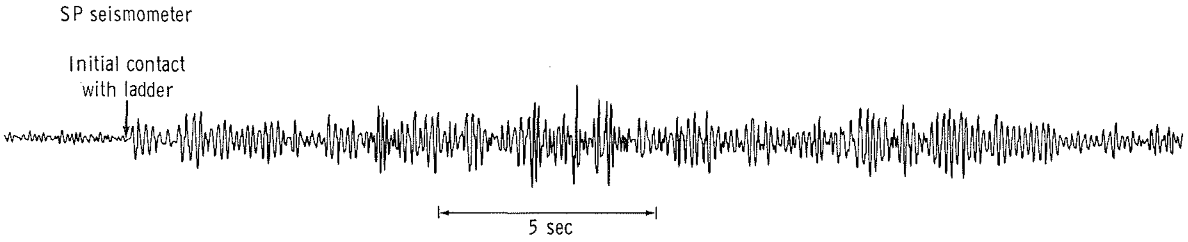

FIGURE 6-7. — Signal recorded when Astronaut Armstrong ascended the ladder of the LM.

in figure 6–7. The spectra of signals from various astronaut activities are shown in figure 6–8. The predominant frequency of all of the type A signals is between 7.2 and 7.3 Hz. This predominant frequency is assumed to correspond to a fundamental mode of vibration of the LM. Three items that were ejected from the LM struck the surface, and the spectra received also contain the 7.2-Hz peak (fig. 6–9). (These items were two portable life support systems, weighing 75 lb each, and the LM armrests, weighing a total of 12 lb.) However, it is important to note that the peaks near 11 and 13 Hz in figure 6–9 would be dominant if the spectra were corrected for instrument response. The spectral peak at 7.2 Hz, perhaps caused by LM resonance, was generated presumably because each ejected item struck the LM porch and ladder while falling to the surface.

In the spectra of signals recorded after the departure of the LM ascent stage, the spectral peak near 7.2 is shifted to 8.0 Hz. Resonances in the LM descent-stage structure, which was left on the lunar surface, would be expected to shift to higher frequencies when the mass of the ascent stage was removed.

The spectrum of one sample of signals from astronaut activity that was performed while the astronaut was not in contact with the LM is included in figure 6–8 for comparison with activities that were performed in physical contact with the LM. In the spectrum of sample (h) of figure 6–8, Astronaut Armstrong was collecting rock samples in the vicinity of the seismometers. The relative spectral content at higher frequencies (10 to 15 Hz) is greater for the sample (h) spectrum than for the other samples. Seismic signals in this frequency range can thus be attributed to astronaut footfalls on the lunar surface.

*Type B.* When the PSEP was turned on, type B signals with very large amplitudes were present on the SP seismometer record. The signals gradually decreased over a period of 8 days, until they disappeared completely on July 29, 1969. Maximum signal levels of approximately 200 m$\mu$m were recorded during the initial stages of activity. Type B signals are shown in figures 6–5 and 6–10. The sections of the record that are shown in figure 6–10 were recorded during the final stages of activity. After a puzzling sequence of changes in pattern, the signals became repetitive with nearly identical structure from train to train. The interval between events generally decreased to approximately 30 sec near their termination. Type B signals reappeared for a period of 13 hr during the second lunar day (13:00 hr on August 21, 1969, to 02:00 hr on

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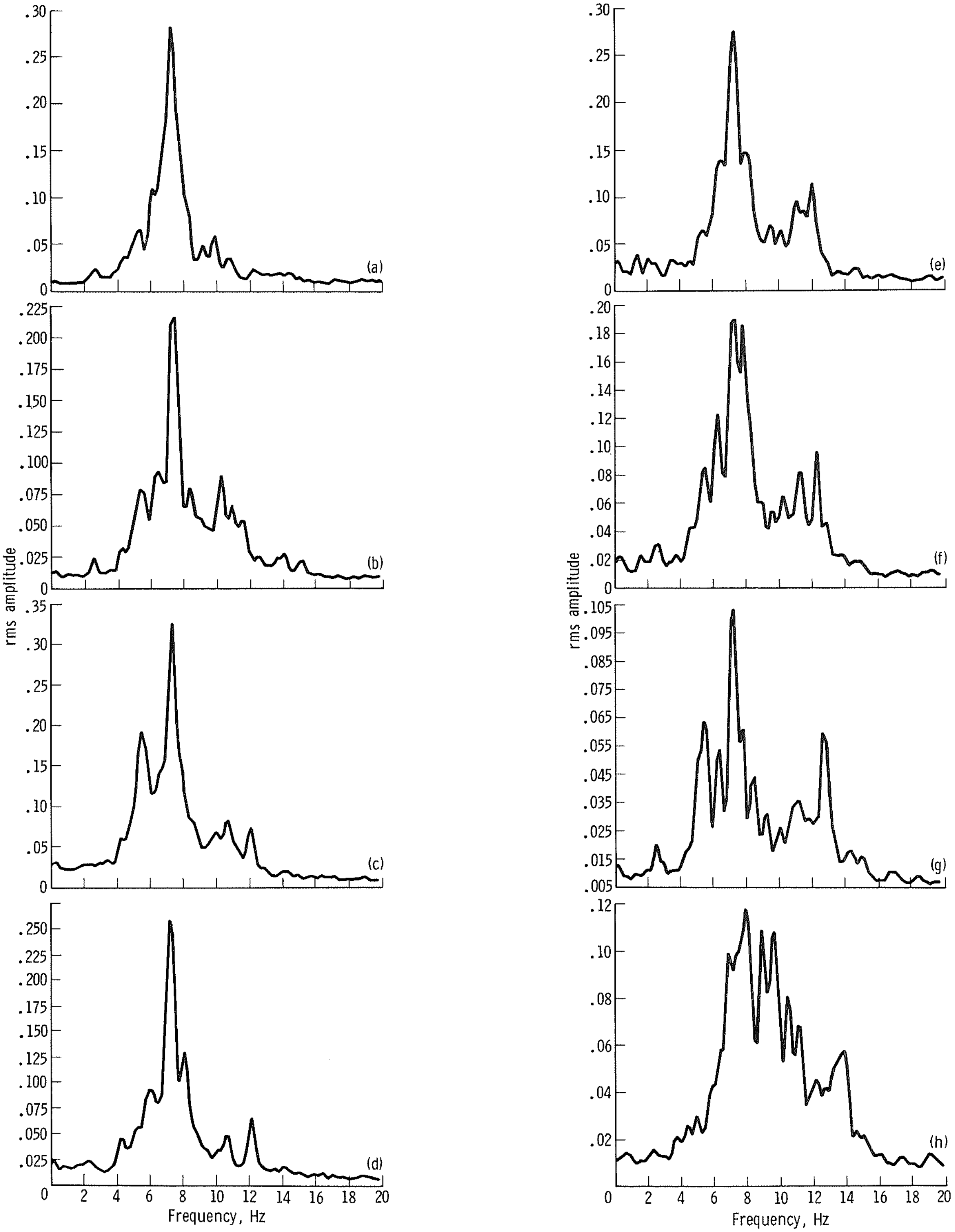
FIGURE 6-8. — Spectra of signals recorded by the SP seismometer during various astronaut activities: (a) Astronaut Aldrin ascending LM ladder, (b) Astronaut Armstrong ascending LM ladder, (c) reaction-control-thruster test firing (first quad), (d) reaction-control-thruster test firing (second quad), (e) impact of the second portable life support system, (f) impact of the first portable life support system, (g) impact of the LM armrests, and (h) Astronaut Armstrong collecting samples in the vicinity of PSEP. Spectra are not corrected for instrument response.


rms amplitude
(a)
.30
.25
.20
.15
.10
.05
0
(b)
.225
.200
.175
.150
.125
.100
.075
.050
.025
0
(c)
.35
.30
.25
.20
.15
.10
.05
0
(d)
.250
.225
.200
.175
.150
.125
.100
.075
.050
.025
0
2
4
6
8
10
12
14
16
18
20
Frequency, Hz
(e)
.30
.25
.20
.15
.10
.05
0
(f)
.20
.18
.16
.14
.12
.10
.08
.06
.04
.02
0
(g)
.105
.095
.085
.075
.065
.055
.045
.035
.025
.015
.005
(h)
.12
.10
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.06
.04
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18
20
Frequency, Hz

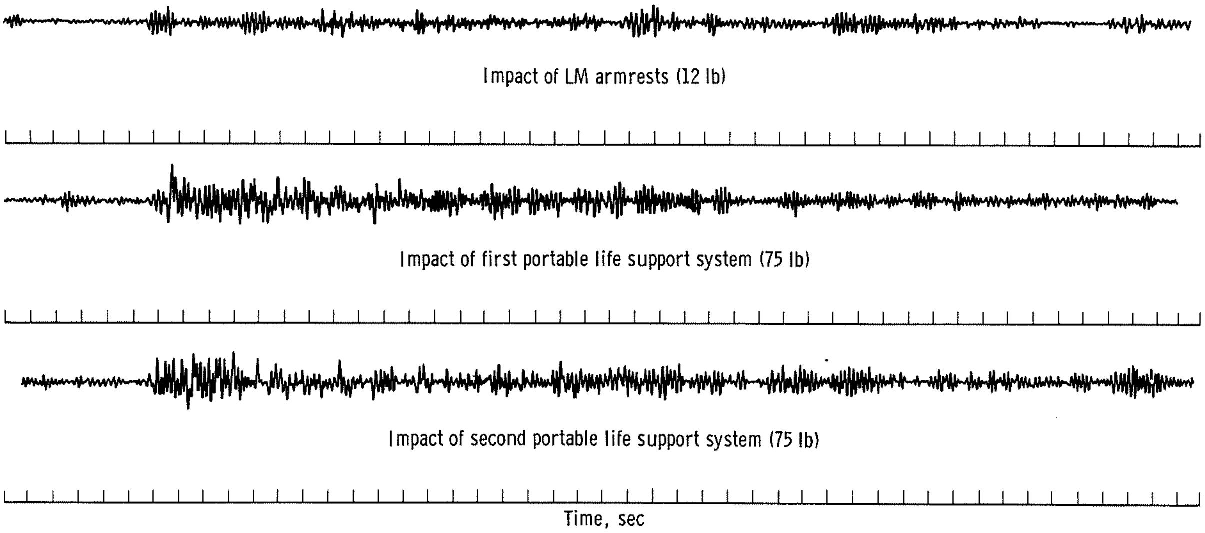


FIGURE 6-9. – Seismic signals recorded by the SP seismometer when various objects ejected from the LM struck the lunar surface.

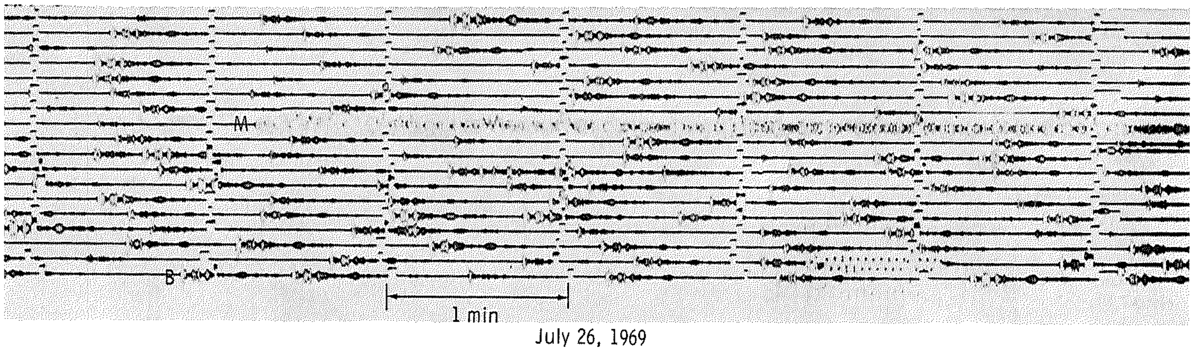


FIGURE 6-10. – Real-time record section from the SP seismometer showing type B and type M signals.

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

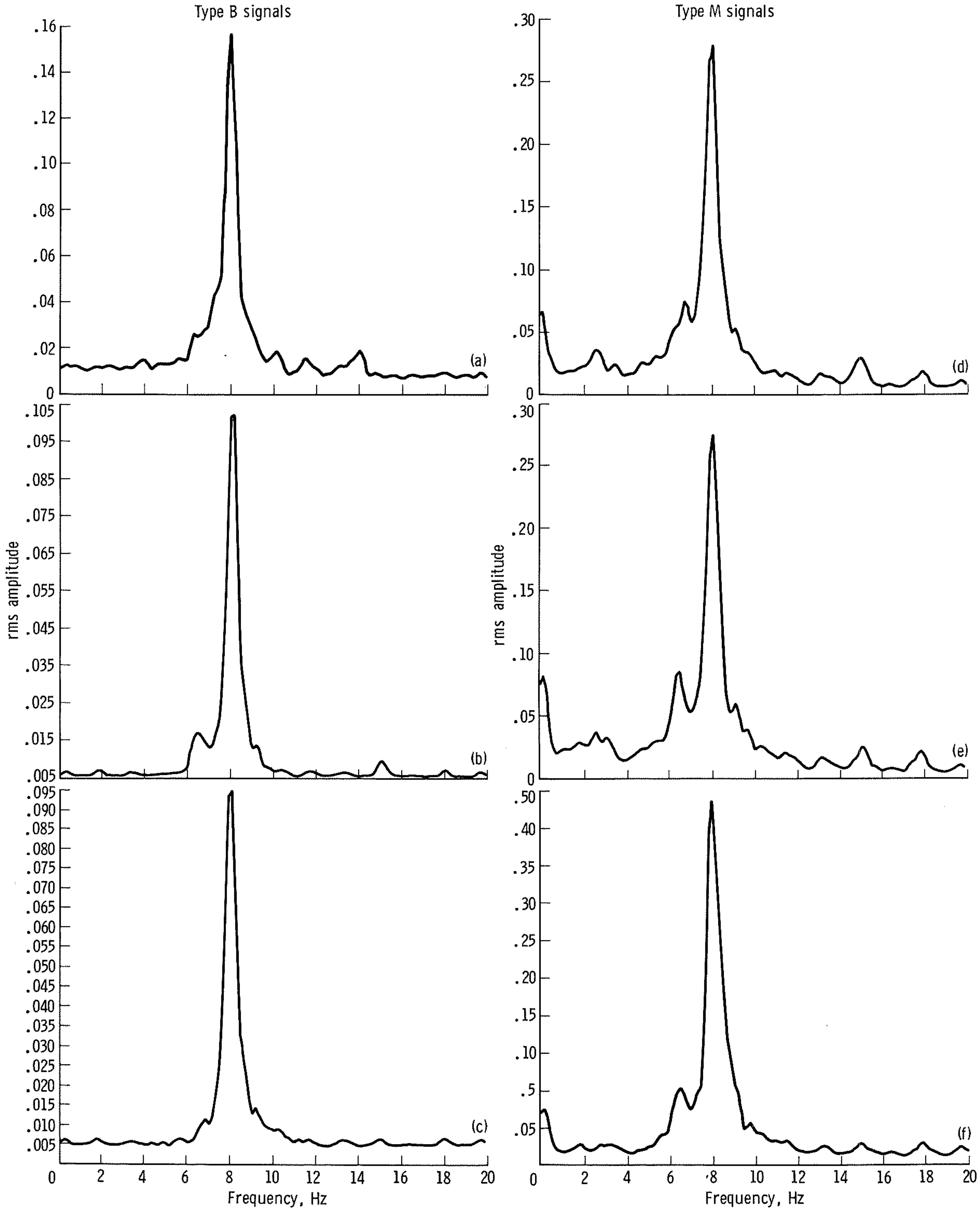


FIGURE 6-11. — Spectra of type B signals (samples (a), (b), and (c)) and type M signals (samples (d), (e), and (f)). Spectra are not corrected for instrument response.

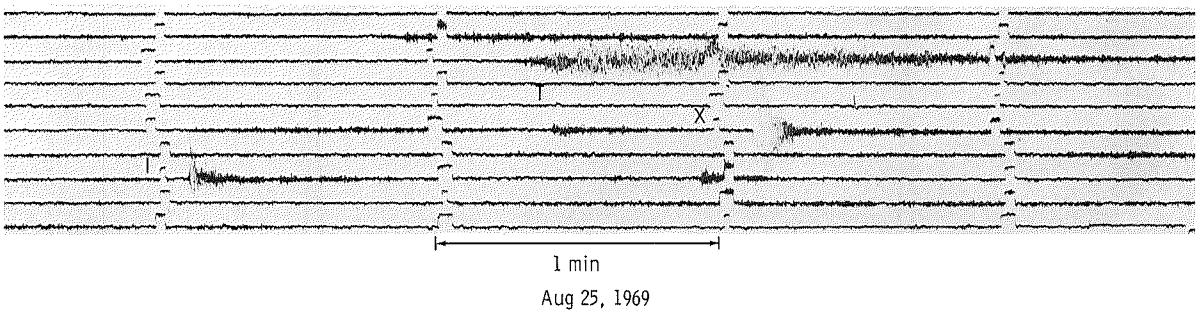


FIGURE 6-12. – Real-time record section of type T, I, and X signals from the SP seismometer.

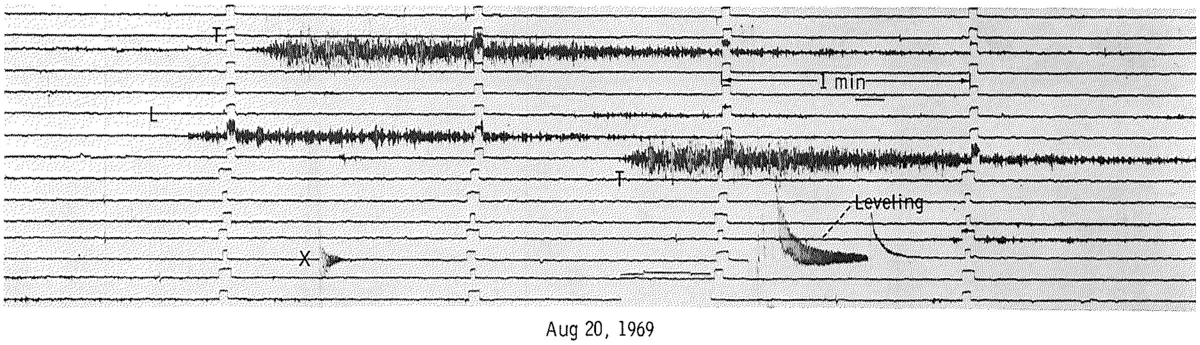


FIGURE 6-13. – Real-time record section of type T, L, and X signals from the SP seismometer.

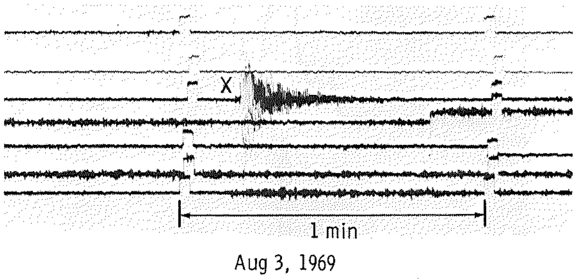


FIGURE 6-14. – Real-time record section of a type X signal from the SP seismometer.

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 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

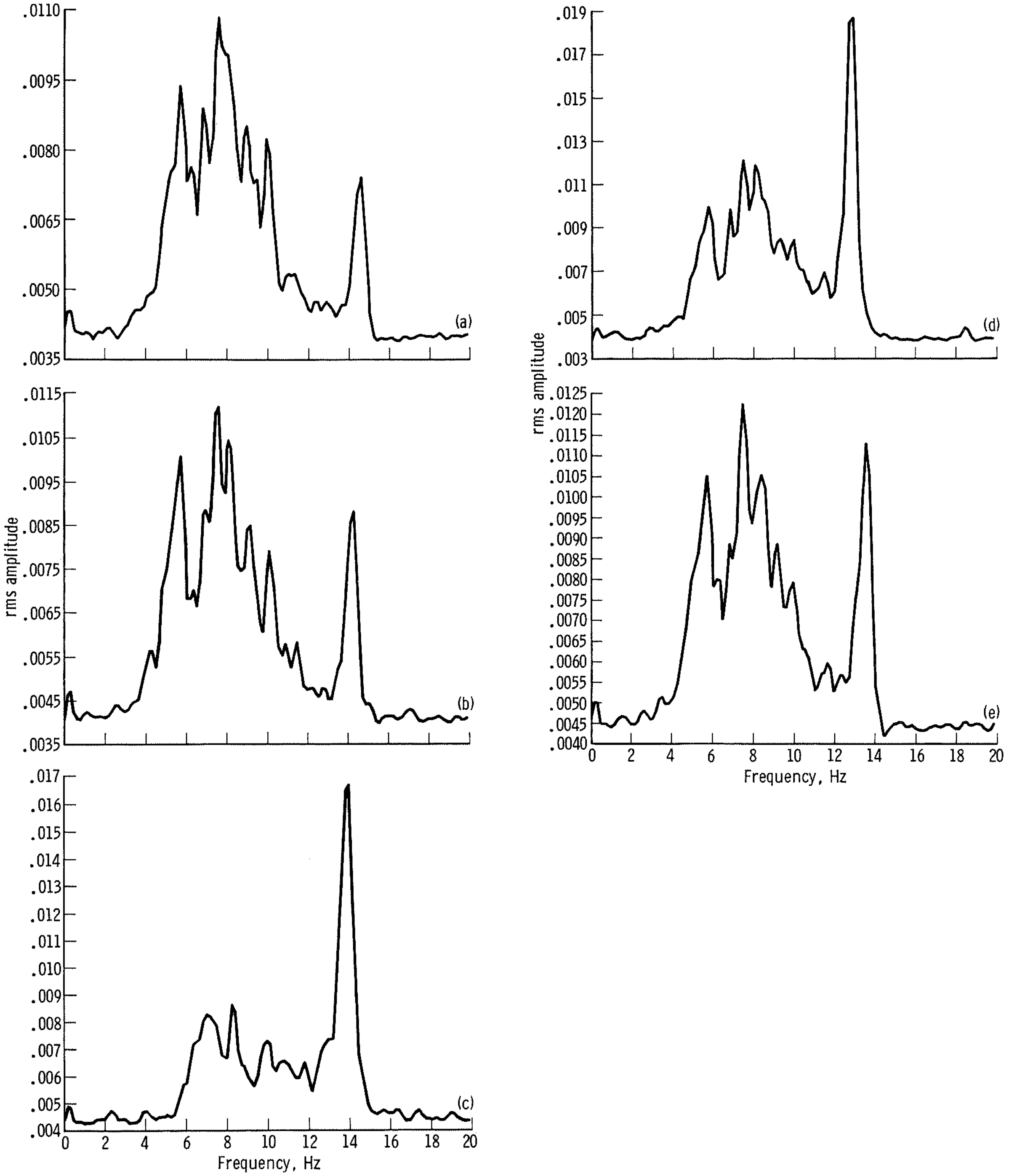
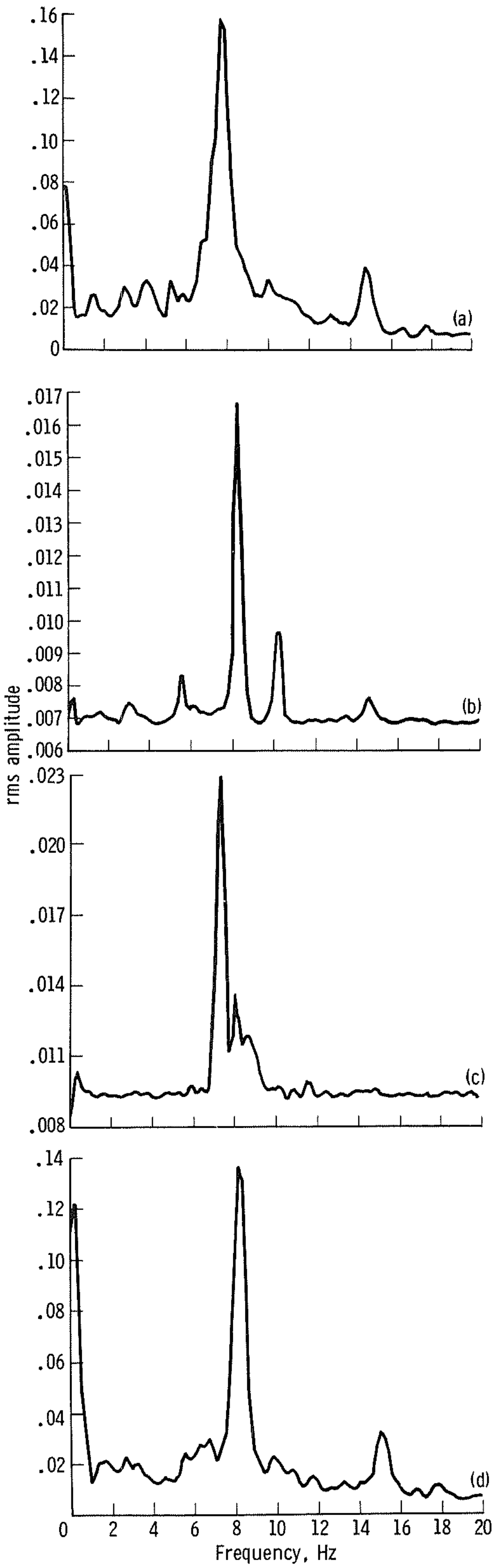


FIGURE 6-15. — Spectra of five type T signals. Spectra are not corrected for instrument response.

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-



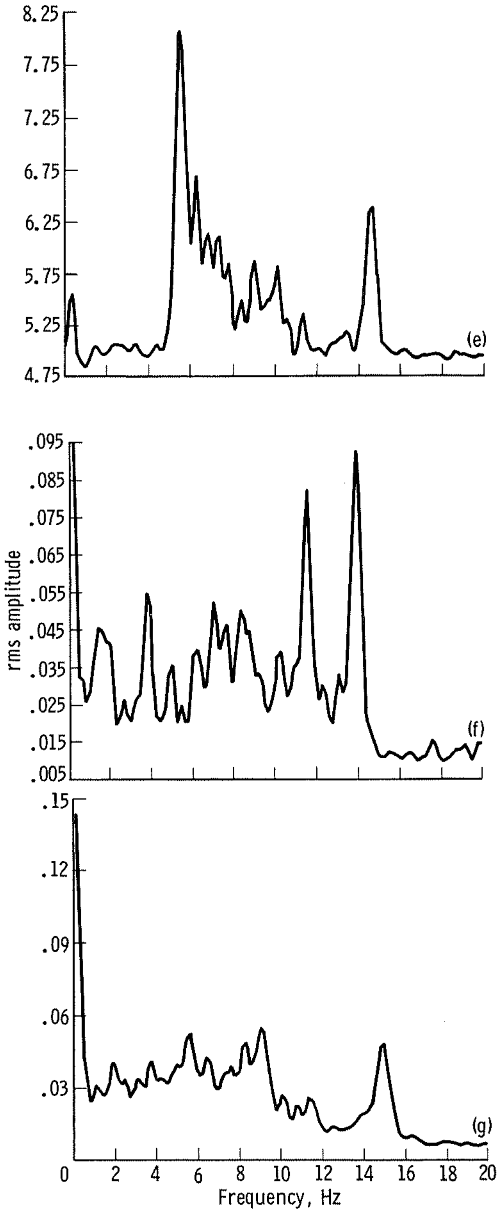


FIGURE 6-16. — Spectra of seven type I signals. Spectra are not corrected for instrument response.

sible sources for 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 mμm 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-

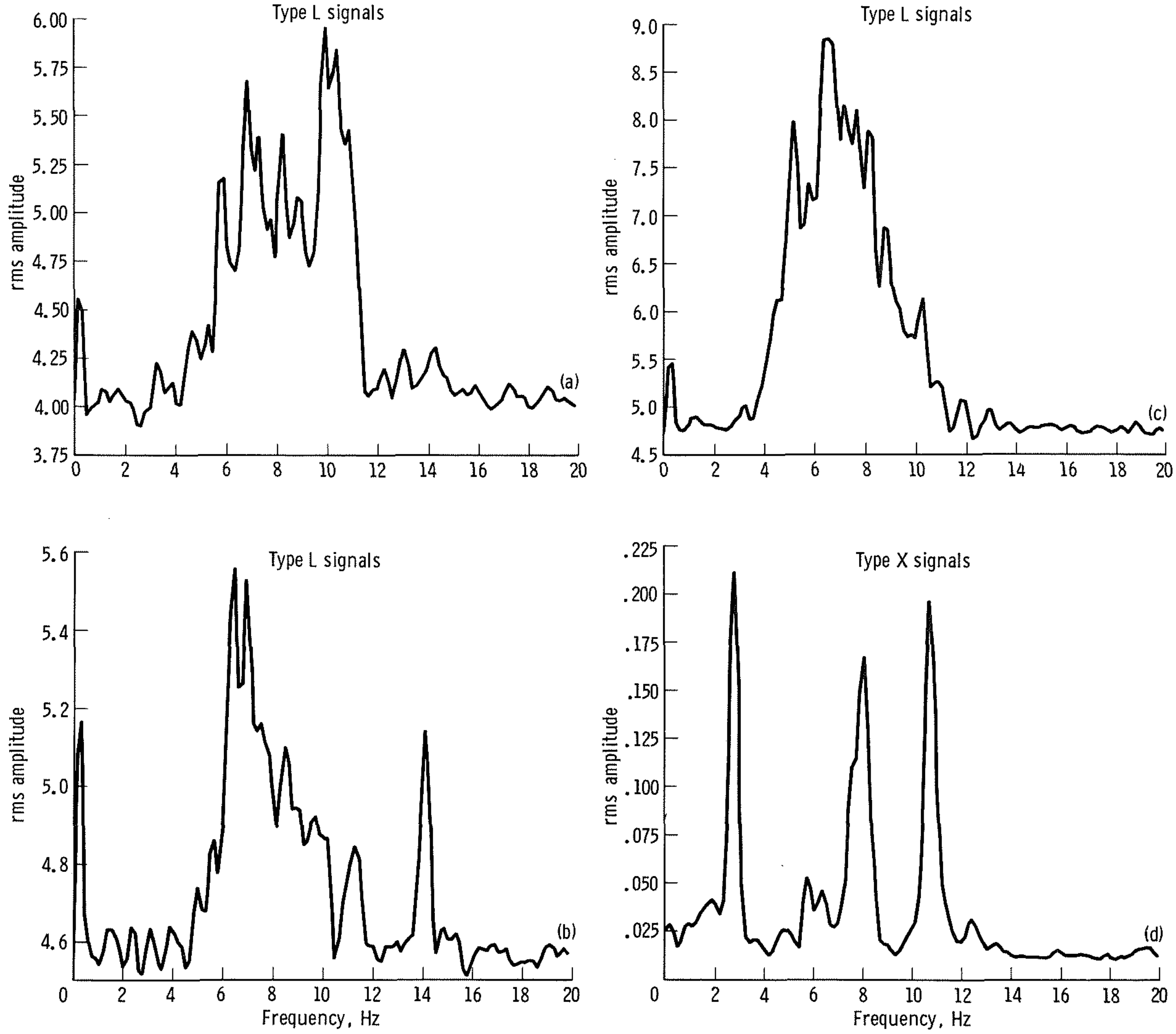


FIGURE 6-17. — Spectra of type L signals (samples (a), (b), (c)) and type X (sample (d)) signals. Spectra are not corrected for instrument response.

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).

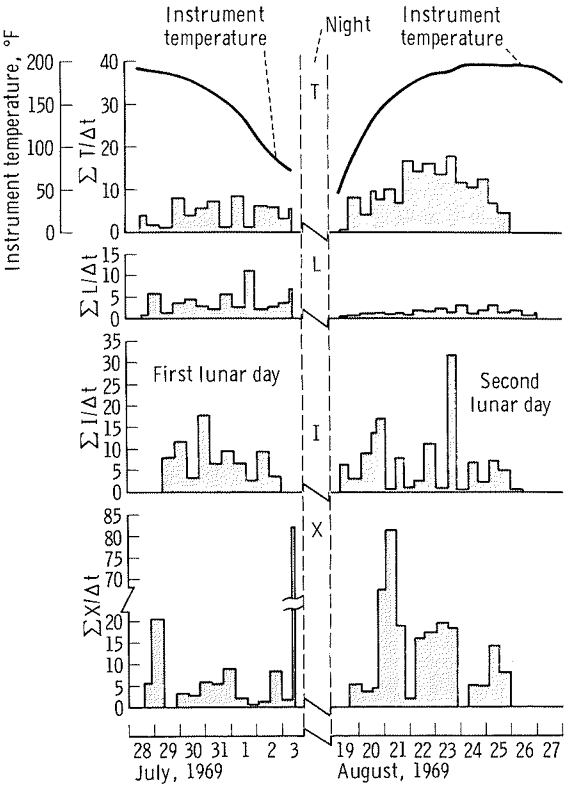


FIGURE 6-18. — A histogram of the intensity of activity for type X, I, T, and L signals.

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 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 $2 \times 10^{-7}$ 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 $\mu$rad for the $y$-axis seismometer and 825 $\mu$rad for the $x$-axis seismometer. The expected peak-to-peak tidal variations are approximately 1 arcsec (4.9 $\mu$rad) 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-

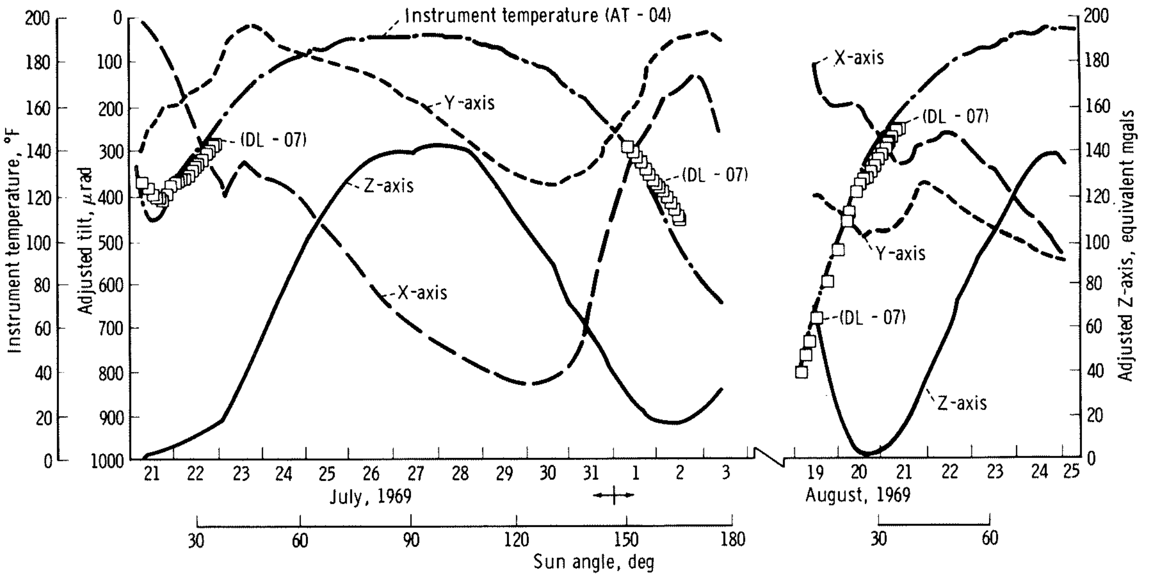


FIGURE 6-19. — Variations in feedback signals and instrument temperature over the 21-day recording period.

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 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 m$\mu$m, which corresponds to system noise. Maximum signal levels of 1.2 $\mu$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 m$\mu$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 m$\mu$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 periods (less than 10 sec) also appears to be less than 0.3 m$\mu$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.

Among the possible explanations of low seis-

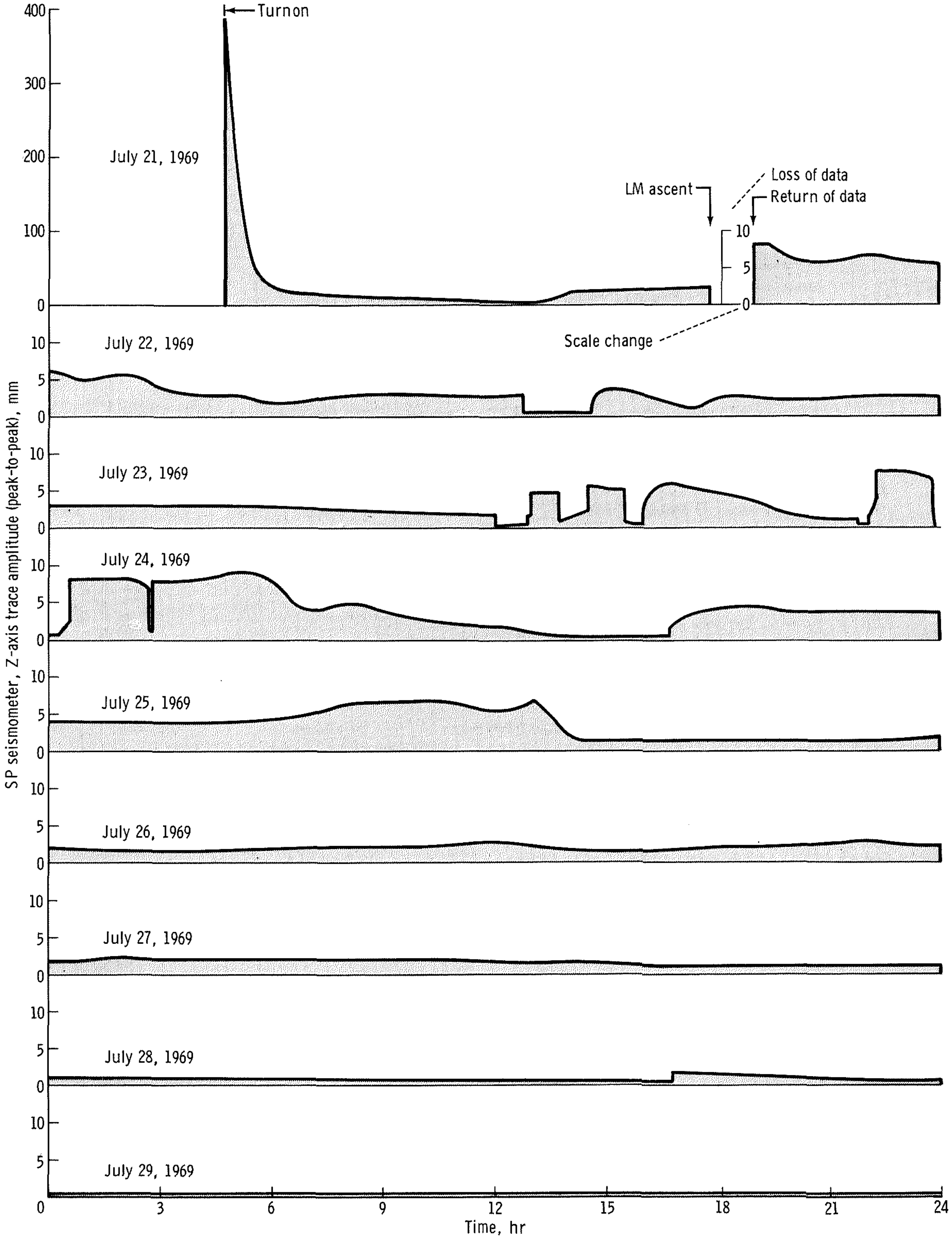


FIGURE 6-20. — Histogram of signal level from the SP seismometer. A 1-mm trace amplitude equals 1.9 m$\mu$m for the predominant signal component (8 Hz).

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

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