7. Active Seismic Experiment

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The purpose of the active seismic experiment (ASE) is to generate and monitor seismic waves in the lunar near surface and to use these data to study the internal structure of the Moon to a depth of approximately 460 m (1500 ft). Two seismic energy sources are used: an astronaut-activated thumper device containing 21 small explosive initiators and a mortar package containing four high-explosive grenades. The grenades are rocket launched by command from Earth and are designed to impact at ranges of about 150, 300, 900, and 1500 m (about 500, 1000, 3000, and 5000 ft). A secondary objective of the experiment is to monitor high-frequency seismic activity during periodic listening modes.

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Analysis to date of the seismic signals generated by the astronaut-activated thumper has revealed important information concerning the near-surface structure of the Moon. Two compressional wave (P-wave) seismic velocities were measured at the Fra Mauro site. The near-surface material possesses a seismic-wave velocity of 104 m/sec (340 ft/sec). Underlying this surficial layer at a depth of 8.5 m (28 ft), the lunar material has a velocity of 299 m/sec (980 ft/sec). The measured thickness of the upper unconsolidated debris

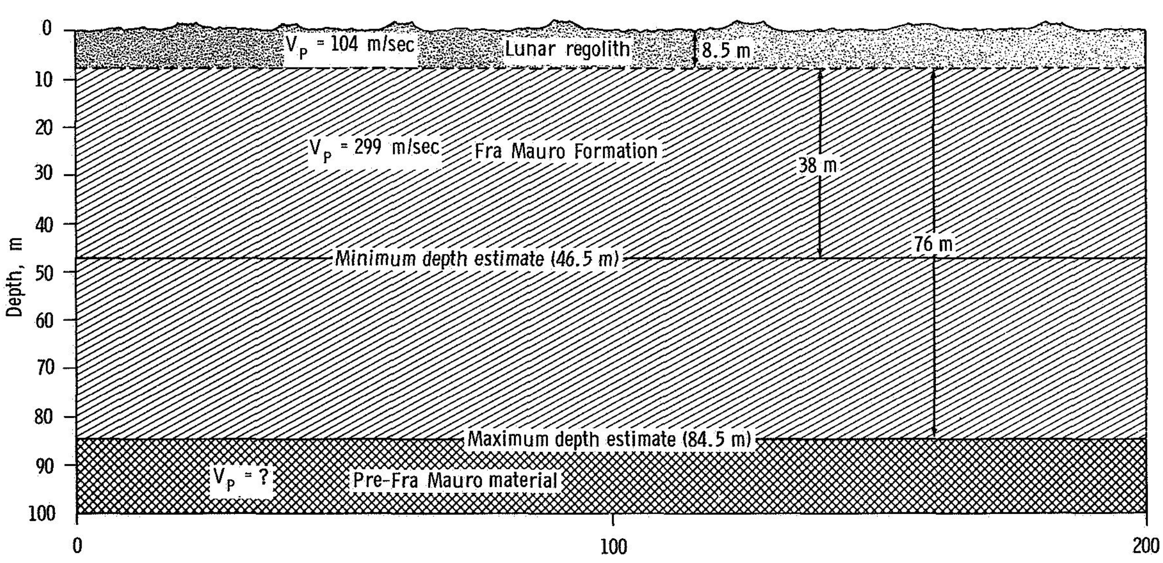

FIGURE 7–1.—Seismic cross section at Fra Mauro landing site. (V_P = seismic-wave velocity.)

layer is in good agreement with geological estimates of the thickness of the regolith at this site.

By combining the seismic-refraction results from the ASE with the lunar module (LM) ascent seismic data recorded by the Apollo 14 passive seismic experiment (PSE), estimates of the thickness of the underlying material can be made (fig. 7–1). These estimates range from 38 to 76 m (124 to 250 ft) and may be indicative of the thickness of the Fra Mauro Formation at this particular site. More definitive conclusions must await the seismic results from the four grenade firings.

Interesting signals, similar to some events recorded by the PSE, have also been recorded during the intermittent passive listening periods of the ASE. Analysis of these signals together with similar data from the PSE may shed light on the origin of these signals.

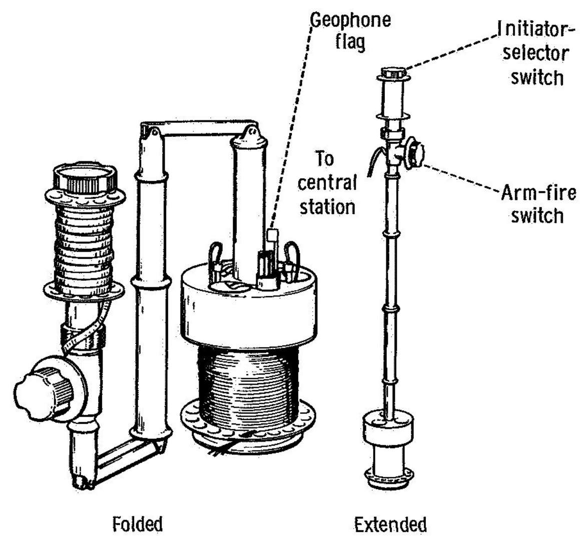

FIGURE 7–3.—Schematic diagram of the thumper in the folded and extended positions.

Instrument Description and Performance

The ASE consists of a thumper and geophones, a mortar package assembly, electronics within the Apollo lunar-surface experiments package (ALSEP) central station, and interconnecting cabling. The components of the ASE are shown schematically in figure 7–2.

The astronaut-activated thumper is a short staff (fig. 7–3) used to detonate small explosive charges—single bridgewire Apollo standard initiators. Twenty-one initiators are mounted perpendicular to the base plate at the lower end of the staff. A pressure switch in the base plate detects the instant of initiation. An arm-fire switch and an initiator-selector switch are located at the upper end of the staff. A cable connects the thumper to the central station to transmit real-time event data. The thumper also stores the three geophones and connecting cables until deployment on the lunar surface. In figure 7–4, the lunar module pilot (LMP) is shown beginning to unwind the

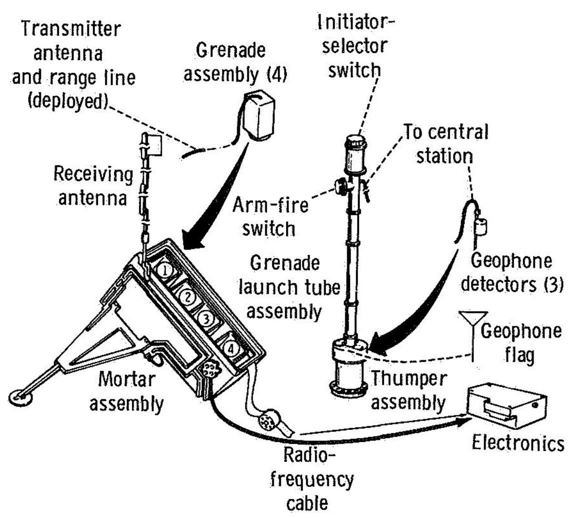

FIGURE 7–2.—Schematic diagram of the ASE.

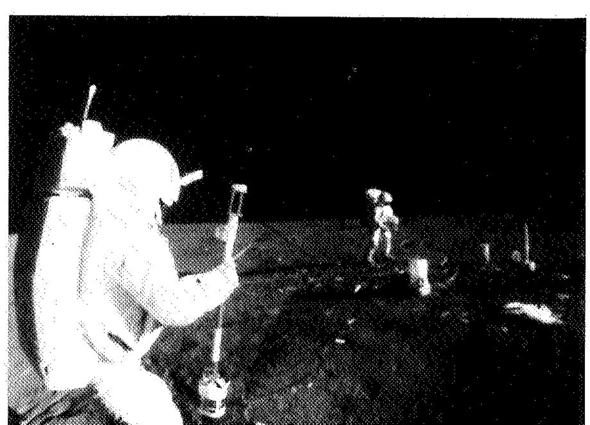

FIGURE 7–4.—Enlargement of 16-mm sequence camera photograph showing the LMP with hand-held thumper (S–71–19509).

geophone line from the thumper on the Moon just before activation of the ASE at 17:59 G.m.t. on February 6, 1971.

The three identical geophones are miniature seismometers of the moving coil-magnet type. The coil is the inertial mass suspended by springs in the magnetic field. Above the natural resonant frequency of the geophones (7.5 Hz), the output is proportional to ground velocity. The geophones are deployed at 3-, 49-, and 94-m (10-, 160-, and 310-ft) intervals in a linear array from the central station and connected to it by cables.

A three-channel amplifier and log compressor condition the geophone signals before conversion into a digital format for telemetering to Earth. The low signal-to-noise ratios expected and the lack of knowledge as to the character of the expected waveforms made it desirable to widen the frequency response as much as possible within the constraints of the digital sampling frequency of 500 Hz. Because signal levels were expected to be distributed throughout the system dynamic range, a logarithmic compression scheme was selected to give signal resolution as some constant fraction of signal amplitude. The system deployed on the Moon has the properties listed in table 7–I, and

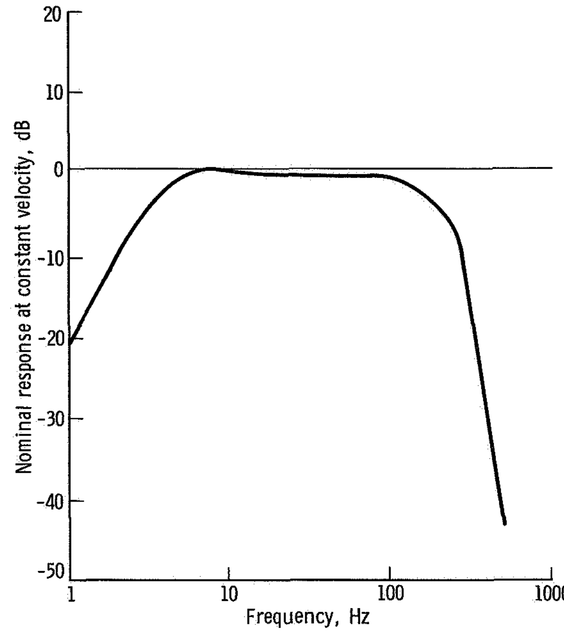

FIGURE 7–5.—Frequency response of the ASE.

TABLE 7–I. *Apollo 14 ASE Characteristics*

Component characteristics	*Channel no.*		
	1	*2*	*3*
Geophones:			
Generator constant, V/m/sec	250.4	243.3	241.9
Frequency, Hz	7.32	7.22	7.58
Resistance, ohm	6065	6157	6182
Amplifiers:			
Noise level, μV rms at input	0.300	0.325	0.272
Dynamic range, rms signal to rms noise in dB	86.8	86.5	87.5
Gain (at 10 Hz and V_{input} = 0.005 V rms)	666.7	666.7	675.7
Log compressor (compression accuracy for temperature range 15° to 50° C):			
Positive signal error, percent	3.79	4.71	2.00
Negative signal error, percent	2.07	1.32	3.33
System:			
Signal-to-noise ratio (rms signal to rms noise in dB for a 1-nm peak-to-peak signal at 10 Hz)	33.6	33.1	32.9
Calibrator accuracy:			
Generator constant, percent error	4.21	9.70	6.40
Natural frequency, percent error	3.28	4.99	8.58

TABLE 7–II. *Apollo 14 ASE Grenade Parameters*

Parameter	Grenade no.			
	1	2	3	4
Range, m	1 500	900	300	150
Mass, g	1 236	1 020	810	719
High-explosive-charge mass, g	454	272	136	45.4
Rocket-motor mean peak thrust, N	20 460	11 450	7005	5337
Mean velocity, m/sec	49	40	23	16
Lunar flight time, sec	44	32	19	13
Rocket-motor-propellant mass, g	47	31	16.8	11.5
Quantity of propellant pellets, number	2 435	1 596	648	550
Launch angle, deg	45	45	45	45
Rocket-motor thrust duration, msec	7.0	8.2	12.5	12.5

the nominal frequency response shown in figure 7–5.

The mortar assembly comprises a mortar box, a grenade-launch-tube assembly, and interconnecting cables. To provide an optimum launch angle for the grenades, the mortar package is deployed at an angle approximately 45° to the lunar surface. A two-axis inclinometer provides pitch- and roll-angle (deviation from the vertical) information on the mortar package. The mortar box is a rectangular fiber-glass-and-magnesium construction in which is mounted the grenade-launch-tube assembly containing four grenades.

Each grenade is attached to a range line, which is a thin-stranded cable wound around the outside of the launch tube. Two fine copper wires are looped around each range line. The first loop is spaced so that it will break when the grenade is approximately 0.4 m (16 in.) from the launch tube. A second loop is spaced to break when the range line has deployed an additional 8 m (25 ft) from the first breakwire. Breaking the loops starts and stops a range-gate pulse to establish a time interval for the determination of the initial grenade velocity.

The four grenades are similar but differ in the amount of propellant and high explosive (table 7–II). Each grenade possesses a square cross section with a thin fiber-glass casing. The casing contains the rocket motor, safe slide plate, high-explosive charge, ignition and detonation devices, thermal battery, and a 30-MHz transmitter. The range line is attached to the transmitter to serve as a half-wave end-feed antenna.

In operation, an arm command from ground control applies a pulse to charge condensers in the mortar box and grenade; a fire command discharges the condenser through an initiator, which ignites the rocket motor. When the grenade leaves the tube, a spring-ejected safe slide is removed, activating a microswitch in the grenade.

A thermal battery and the electronics in the grenade make up the firing circuit. The microswitch discharges a condenser across a thermal match to activate the thermal battery, which in turn powers the transmitter and produces a capacitor charge for the detonator. At impact, an omnidirectional impact switch closes, discharging the capacitor into the detonator to ignite the explosive. The explosion terminates radiofrequency transmission as an indication of detonation time. The critical parameters measured are the detonation time, time of flight, initial velocity, and launch angle. Because of the ballistic trajectory followed by the grenades in the lunar vacuum, the necessary data are available to determine grenade range. The planned mortar mode of operation for the ASE is shown in figure 7–6.

Because some of the geophone parameters might drift on the lunar surface, a calibrator circuit is provided in the system to measure these parameters to within 10 percent of the preflight values. The damping resistance across the geophone is altered to underdamp the geophone, and

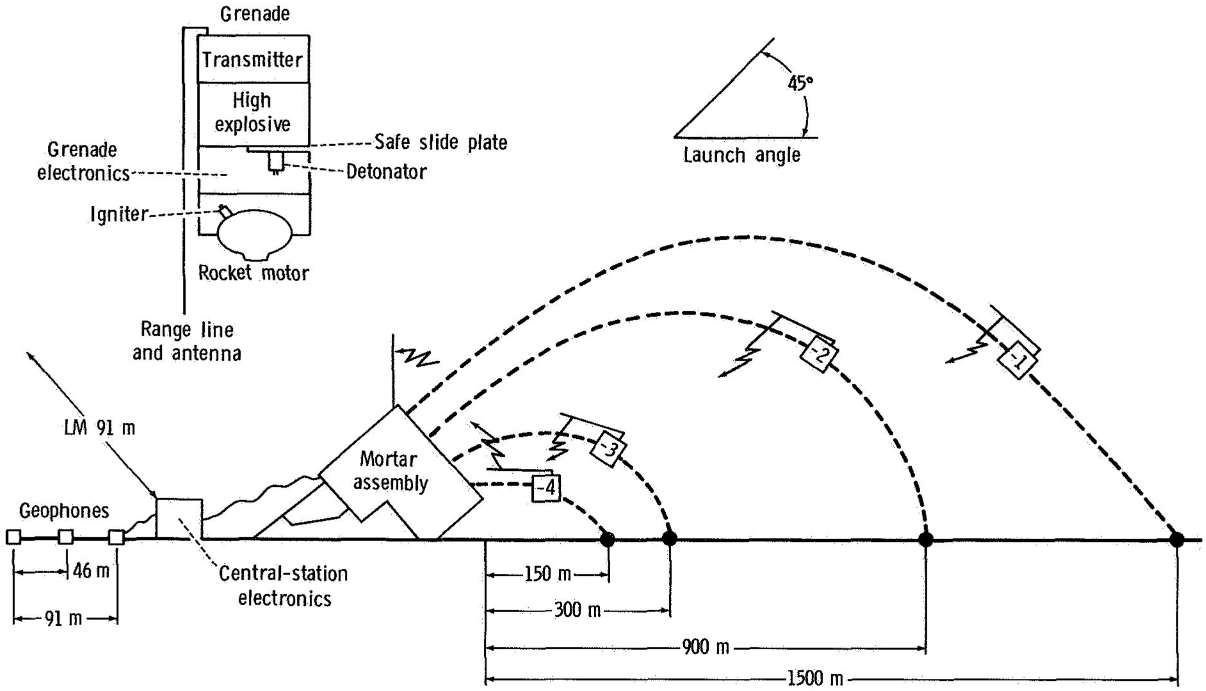

FIGURE 7–6.—Schematic diagram showing the mortar mode of operation for the ASE.

current is introduced into the geophone coil to react with the magnetic field of the geophone, producing a force on the geophone coil. This force moves the coil and, with an underdamped geophone, the signal from the geophone is a logarithmically decaying sinusoidal signal. A typical calibration pulse recorded on the three geophones on February 12 is shown in figure 7–7. Analysis of similar calibration pulses transmitted between thumper operations on the Moon demonstrated close agreement of the natural frequency and generator constant of the geophones with measured preflight values.

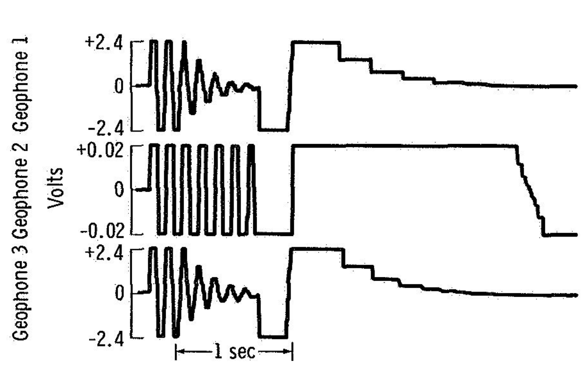

FIGURE 7–7.—Calibration pulse recorded on February 12 during passive listening mode.

The ASE system is controlled from Earth by a number of commands that control such functions as switching to the high-bit data rate and firing the grenades from the mortar box assembly. Further technical details of the ASE, particularly of the electronics, can be found in reference 7–1.

Thermal Control

The ASE electronics are part of the ALSEP central station and do not require separate thermal control. The ASE mortar package assembly was designed to be maintained between —60° and 85° C. Thermal control of the mortar package assembly is accomplished with multilayer aluminized Mylar insulation used in conjunction with small heaters. Heater operation begins automatically at a temperature of about —17° C when the ASE is in the standby mode of operation. Four temperatures are monitored in this mode: central-electronics temperature, grenade-launch-tube-assembly temperature, mortar-package temperature, and temperature of the geophone closest to the ALSEP.

Deployment

At the Apollo 14 site, the three geophones are alined in a southerly direction from the ALSEP central station (fig. 3–1 in sec. 3). No difficulty was experienced in deploying and arming the mortar package. The mortar package is positioned to fire the four grenades in a northerly direction in alinement with the geophone line. The mortar package assembly is shown in figure 7–8 as deployed on the lunar surface. A view looking downrange from the mortar package is shown in figure 7–9. The geophone line appears in the right foreground.

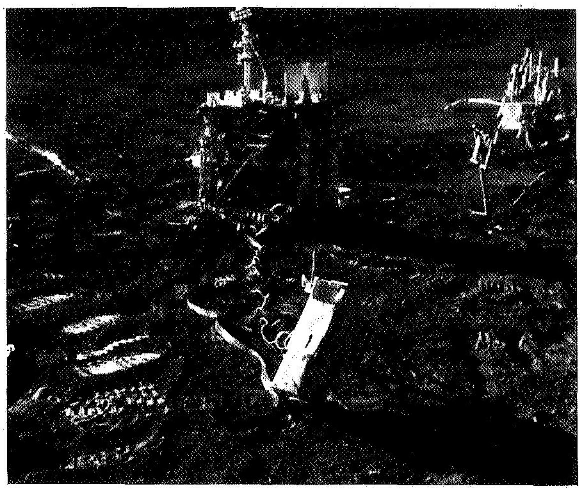

FIGURE 7–8.—Mortar assembly deployed on the lunar surface (AS14–67–9361).

For convenience, the geophone closest to the ALSEP is designated "geophone 1" and the most distant is designated "geophone 3." No difficulty was experienced in implanting the geophones and maintaining them vertically in the lunar soil. Before beginning thumper operations at geophone 3, it was noted that the alinement flag at geophone 2 had fallen over. Because of time constraints, thumper operations were begun at geophone 3 before returning to check the flag and geophone at the middle position.

Thumper operations were begun at 18:09 G.m.t. and continued until 18:37 G.m.t. Thumper firings were begun with shot 1 at geophone 3 and continued at 4.6-m (15-ft) intervals along the geophone line to shot 21 at geophone 1. In figure 7–10, the LMP is shown firing the thumper along the geophone line on the lunar surface. The thumper failed to fire after several attempts at

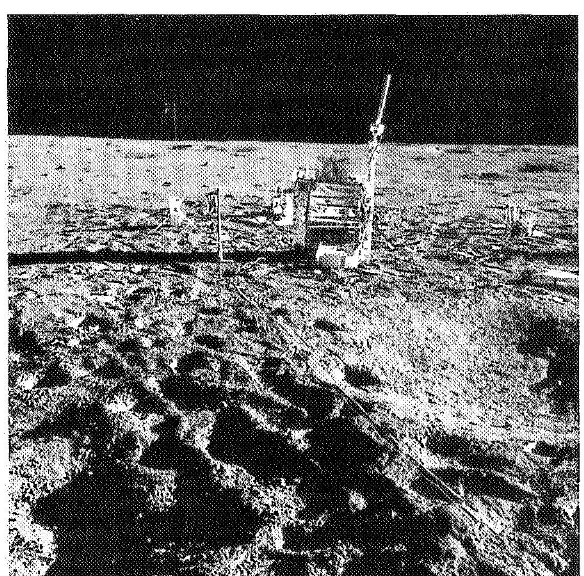

FIGURE 7–9.—Photograph looking downrange from mortar assembly on lunar surface. Geophone line is deployed in right foreground (AS14–67–9377).

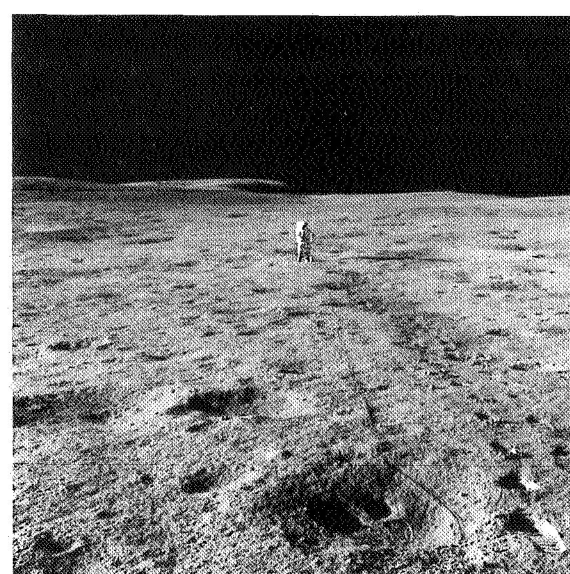

FIGURE 7–10.—The LMP firing thumper along geophone line on the lunar surface (AS14–67–9374).

several initiator positions, and several firing positions were skipped to gain extravehicular activity (EVA) time. Successful thumper shots were recorded at positions 1 (located at geophone 3); 2, 3, 4, 7, 11 (located at geophone 2); 12, 13, 17, 18, 19, 20, and 21 (located at geophone 1).

Upon reaching position 11, at the middle geophone, the LMP observed that this geophone had pulled out of the ground, apparently because of the effects of set or elastic memory in the cable. After repositioning the geophone, he resumed thumping operations. Even though geophone 2 was resting on its side during the first five thumper firings, usable seismic data were recorded. The net result of tipping a vertical-component geophone off vertical is to translate the mass and effectively increase the natural frequency. Analysis of the calibration pulse sent before beginning thumping operations showed that the effective natural frequency of geophone 2 had increased from 7.5 to 13.4 Hz. The total time spent on thumping operations was 28 min, within allowable EVA constraints, and valuable lunar seismic data were obtained.

Several thumper shots were attempted while the commander was moving on the lunar surface near the ALSEP central station. Unfortunately, his movements generated seismic energy that was recorded by the highly sensitive geophones. As a result, his movements had to be restricted during the remaining thumper operations. However, it still may be possible to conduct thumper operations on the Moon and allow the second astronaut to move about, provided he is sufficiently far removed from the central station and geophone line.

Description of Recorded Seismic Signals

Thumper Mode

During thumper operations on the lunar surface, the LMP was instructed to stand still for 20 sec before and 5 sec after each firing. Therefore, 5 sec of seismic data were recorded for each thumper firing. The seismic data recorded for thumper shots 18 and 20 are shown in figure 7–11. Characteristically, the seismic signals produced by thumper firings within 9 m (30 ft) of a geophone have extremely impulsive beginnings and saturate the dynamic range of the amplifier for about 0.5 sec. The predominant frequency of these signals range from 27 to 29 Hz.

As the distance between the thumper firings and the geophones is increased, the seismic signals possess more emergent beginnings. In figure 7–12, a record section is alined in time to the same instant of firing for thumper shots 18 to 21 as recorded at geophone 2. The wave trains build up to a maximum amplitude within the first 0.25 to 0.5 sec from onset of signal and then gradually decrease in amplitude. This effect can best be seen in figure 7–11 by comparing the seismic signals recorded at 14, 32, and 41 m (45, 105, and 135 ft). Little difficulty exists in picking the onset of the seismic signals out to a distance of 46 m (150 ft); but, at greater distances, uncertainty arises in determining the beginning of the seismic wave arrival because the signals are much weaker. The peak amplitude of the recorded signals typically decreases by a factor of approximately 60 in 61 m. More refined data-analysis techniques applied to the recorded seismic signals from the thumper mode of operation are underway.

Passive Listening Mode

The ASE is also capable of operating in a passive listening mode and is commanded into this high-bit-rate mode for a 30-min period each week. Several interesting signals have been recorded in this mode of operation. Two of these events, recorded on February 19, are shown in figure 7–13. The signals have the largest amplitude on a single geophone, although the signal is definitely discernible above the ambient noise level, but greatly reduced in amplitude on the other geophone channels.

The signal recorded on geophone 1 beginning at about 15:29:41 G.m.t. has a predominant frequency of approximately 36 Hz, whereas the signal recorded by geophone 2 at approximately 15:38:46 G.m.t. has a frequency of approximately 47 Hz. Both of these signals have impulsive beginnings and relatively short durations of 6 to 10 sec. Maximum amplitudes occur at the beginning of the wave train.

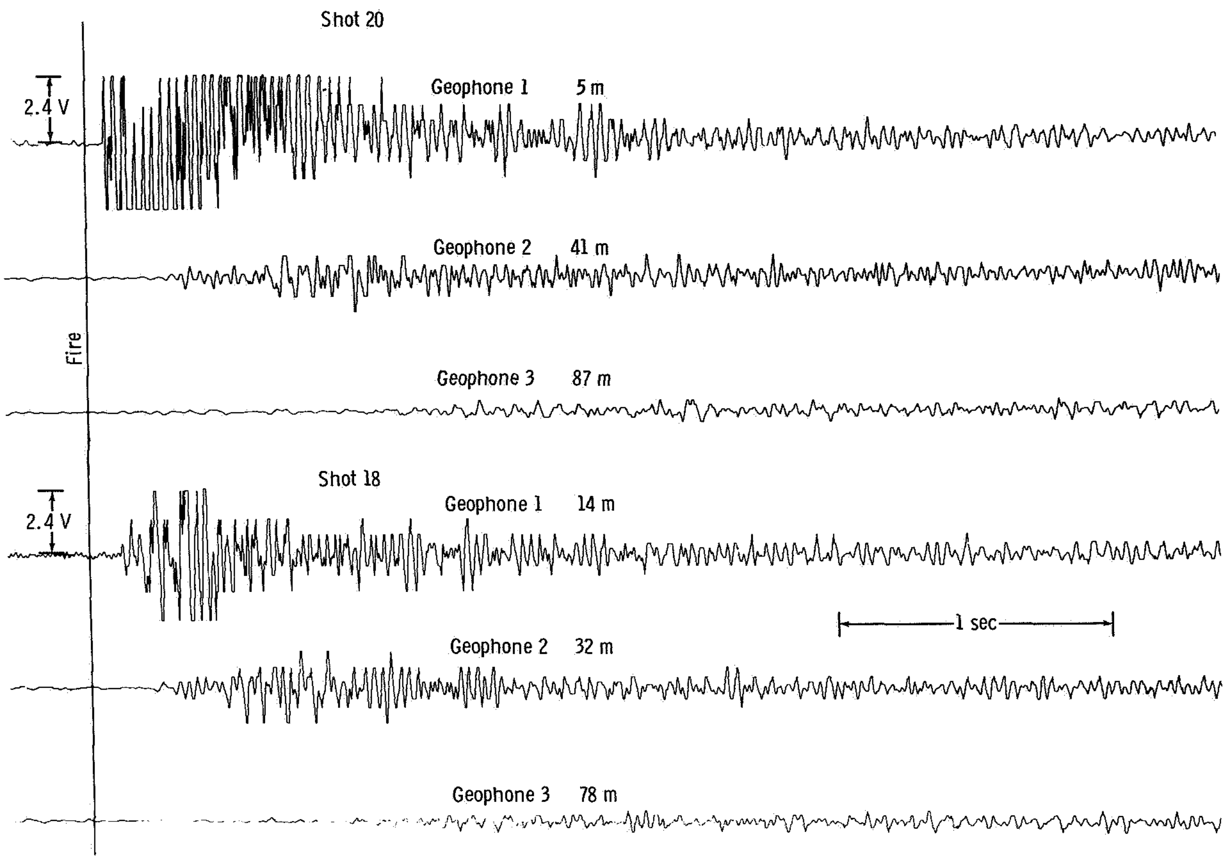

FIGURE 7–11.—Seismic signals produced by thumper firings 18 and 20 on the lunar surface.

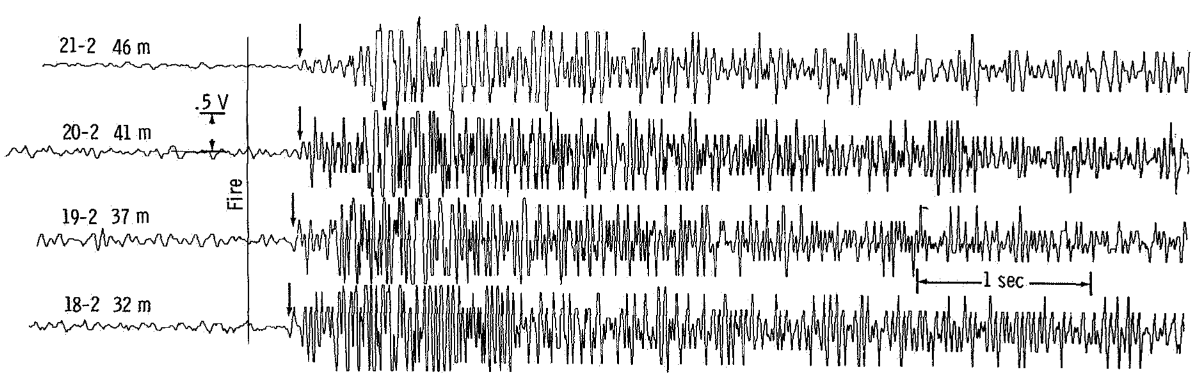

FIGURE 7–12.—Seismic signals produced by thumper firings 18 to 21 as recorded at geophone 2. The traces are alined to the same relative instant of the firing of the thumper. The small arrows point to the onset of the seismic signal.

One can note a gross similarity to the seismic signals produced by thumper firings close to a geophone, although the amplitude of these signals is approximately 100 to 200 times smaller than the thumper-generated signals. These events are also strikingly similar to the type X events (impulsive beginnings and relatively short durations—normally less than 10 sec) recorded during the

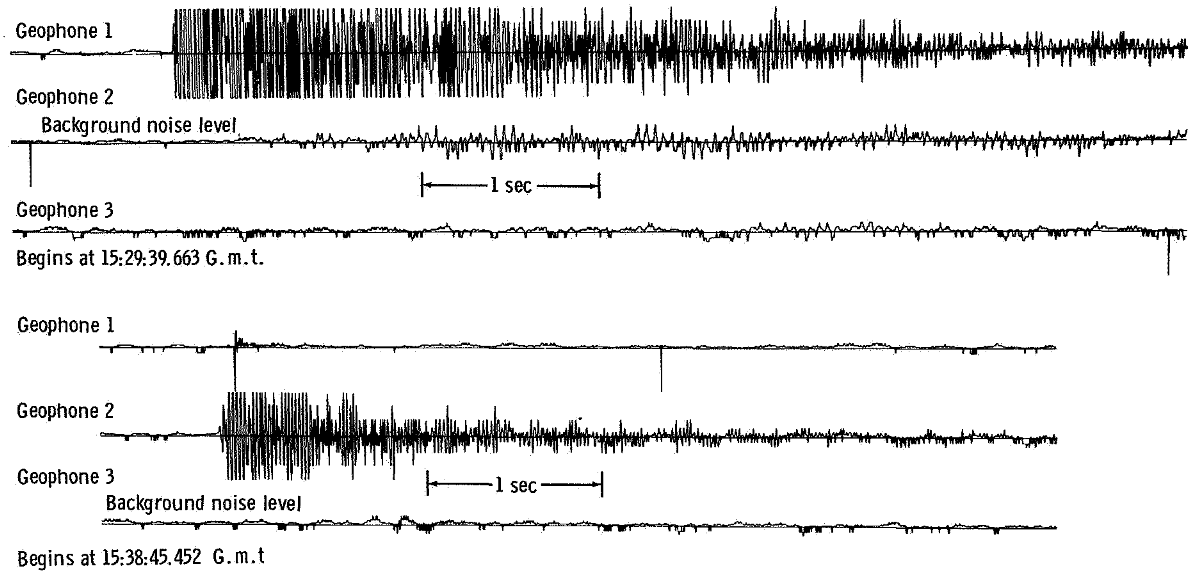

FIGURE 7–13.—Signals recorded during the passive listening mode on February 19; all plots clipped at 0.01 V.

Apollo 11 mission (ref. 7–2) that were speculated to be produced by direct micrometeoroid impacts on the PSE. Continuing work is being directed toward detailed analysis of these events.

Discussion

A preliminary interpretation of the traveltime/distance data (fig. 7–14) obtained from the thumper firings is rewardingly consistent in that

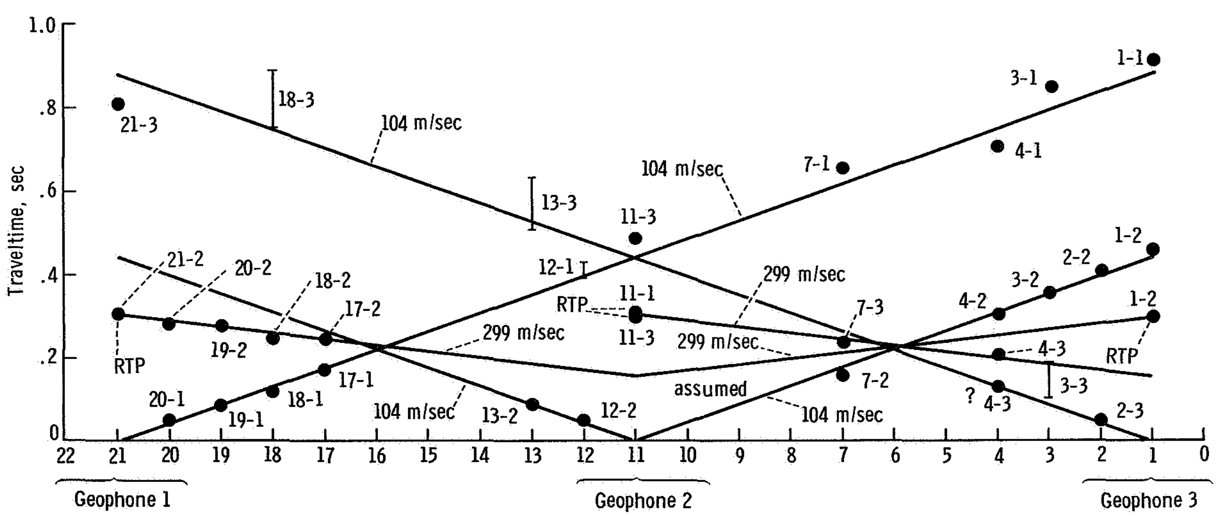

FIGURE 7–14.—Seismic arrivals from the thumper firings plotted on a traveltime/distance graph. The data points are shown as black circles; the first number refers to the thumper firing, the second number to the geophone on which the data were recorded. Reverse tie points are indicated as RTP; distance between thumper shot locations is 4.6 m.

very good agreement exists in reverse tie points (RTP); that is, the principle of seismic reciprocity states that traveltimes must be identical when the positions of a geophone and a shot (thumper firing) are interchanged. For example, the traveltime for thumper shot 21 to geophone 2 and thumper shot 11 to geophone 1 should be identical. The near identity of reverse tie points 21–2 and 11–1 and of 11–3 and 1–2 lends strength to the data interpretation. Agreement between reverse tie points 1–1 and 21–3 is somewhat poorer, but it should be remembered that the more distant thumper firings produced much weaker seismic signals for which it is difficult to determine unambiguously an initial onset. An example of traveltimes that cannot be precisely determined is 18–3, and the range of possible traveltimes is shown by the line.

Two P-wave velocities are evident in the traveltime data. A direct arrival is observed with a P-wave velocity of 104 m/sec together with a faster arrival possessing a velocity of 299 m/sec. No apparent variation exists in P-wave velocities across the section sampled as is evidenced by the conformance of seismic velocities measured along the geophone line.

The depth to the 299-m/sec refracting horizon is 8.5 m. It is proposed that this thin upper layer possessing a seismic velocity of 104 m/sec represents the fragmental veneer of unconsolidated particulate debris—the lunar regolith that covers the surface at the Fra Mauro site. If the discontinuity between the 104-m/sec and the 299-m/sec material is accepted as the base of the regolith, the thickness of the regolith is very similar to that estimated solely on geological evidence. By photographic studies of the depth at which blocky floors appear in fresh craters, it has been inferred that the fragmental, surficial layer that overlies the more consolidated or semiconsolidated substrate at the Fra Mauro site ranges in thickness from 5 to 12 m (ref. 7–3).

From measurement of the elapsed time between engine ignition and signal arrival at the Apollo 12 PSE for the reaction control system test firings and for the LM ascent, the compressional velocity of the lunar-surface material at the Apollo 12 site was determined to be approximately 108 m/sec

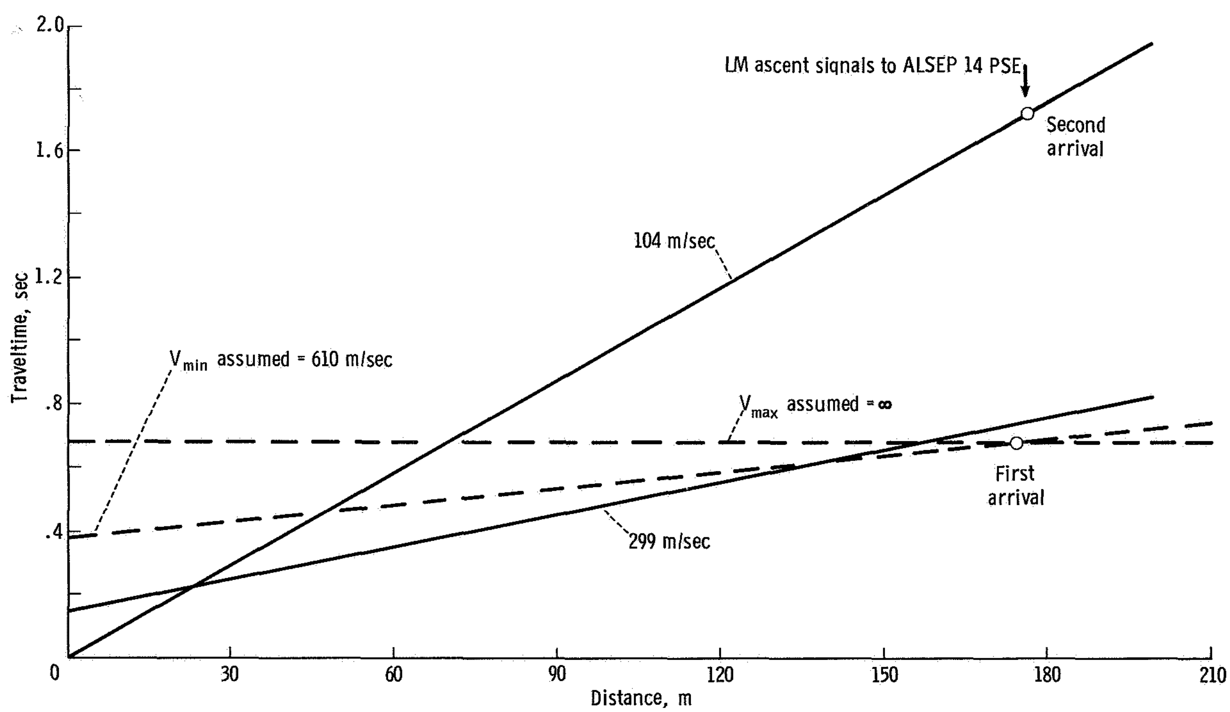

FIGURE 7–15.—First and second arrivals from the LM ascent as recorded by the PSE compared to the extrapolated traveltime/distance data derived from the thumper firings.

(ref. 7–4). This value is in exceedingly close agreement with that measured for the surface material at the Apollo 14 Fra Mauro site and is also consistent with estimates derived on the basis of mechanical properties measured by Surveyor (ref. 7–5). Therefore, it can be argued that the fragmental and comminuted layer that covers much of the lunar surface, although locally variable in thickness, possesses remarkably similar seismic or acoustic properties.

One other piece of evidence lends support to this hypothesis. Seismic signals were also generated by the LM ascent and recorded by the Apollo 14 PSE at a distance of 178 m (584 ft). These data are shown in figure 7–15 compared with the extrapolated traveltime/distance curves derived from the thumper firings of the ASE. The observed traveltime for the second arrival is nearly identical to that predicted for a direct seismic wave propagating with a velocity of 104 m/sec. A first arrival is observed with a traveltime somewhat faster than that predicted by a refraction from the top of the 299-m/sec horizon, suggesting that a material with a faster intrinsic compressional-wave velocity lies beneath the 299-m/sec material.

If the assumption is made that this underlying material possesses an infinite compressional-wave velocity V and that the traveltime curve behaves in the manner shown in figure 7–15, a maximum estimate to the thickness of the 299-m/sec material can be derived. Similarly, if only a modest increase in seismic velocity, such as to 610 m/sec (2000 ft/sec), in the underlying material is proposed, then a minimum estimate is obtained. These assumptions lead to a minimum thickness estimate of 38 m and a maximum thickness estimate of 76 m.

At this writing, it is somewhat premature to speculate what the 299-m/sec material represents other than to comment that this velocity is similar to that measured in situ in blocky basalt flows near Flagstaff, Ariz., or in blocky pumice deposits such as found at the Southern Coulee of the Mono Craters, California (ref. 7–6). However, no inference to a specific rock type should be made because a wide range of velocities is often determined for similar rocks, and similar velocities are often measured for widely different rock types. Nevertheness, it is interesting to point out that the thickness estimate of 38 m to 76 m for this material is not in disagreement with the postulated thickness of 100 m or so for the Fra Mauro Formation (ref. 7–3).

The relatively low compressional wave velocities that were measured by the ASE argue against the presence of substantial amounts of permafrost in the lunar near surface at this particular site. Measured velocities in permafrost vary greatly—depending on such factors as lithology, porosity, and degree of interstitial freezing—but typically range from 2438 to 4572 m/sec (8000 to 15 000 ft/sec) (ref. 7–7).

It has also been proposed (ref. 7–8) that the unconsolidated surface debris layer (the lunar regolith) together with a shattered crystalline layer forms a surface low-velocity zone to "trap" seismic surface waves effectively; this proposal helps to explain the prolonged reverberations recorded by the Apollo 12 PSE after the impact of the Apollo 12 LM and the Apollo 13 SIVB. However, the assumed working model consisted of a 30-m-thick, surface, low-velocity layer overlying crystalline material that has an intrinsic seismic velocity some 20 times greater than that of the surface-debris layer. To date, the results of the ASE argue against this hypothesis on a moonwide basis. Further details concerning the deeper structure of the lunar near surface of the Fra Mauro site must await the results from the ASE grenade firings.

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