The Description of Apollo Seismic Experiments

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(1) Apollo Passive Seismic Experiment (PSE)

[General Description]

Passive seismic stations were installed on the lunar surface during Apollo missions 11, 12, 14, 15 and 16.Station 11 operated only 21 Earth days before the loss of the command uplink terminated its operation. The four remaining stations constitute the Apollo seismic network. This network only covered the front center of the Moon in an approximate equilateral triangle with 1100-km spacing between stations as shown in Figure 1. (Station 12 and 14 are 181 km apart at one corner of the triangle.) This network observation has continued until September 30, 1977. Each passive seismic station consist of three matched long-period seismometers alined orthogonally to measure one vertical (LPZ) and two horizontal components (LPX and LPY) of surface motion. The sensor also includes a single-axis short-period (SPZ) seismometer sensitive to vertical motion at higher frequencies.

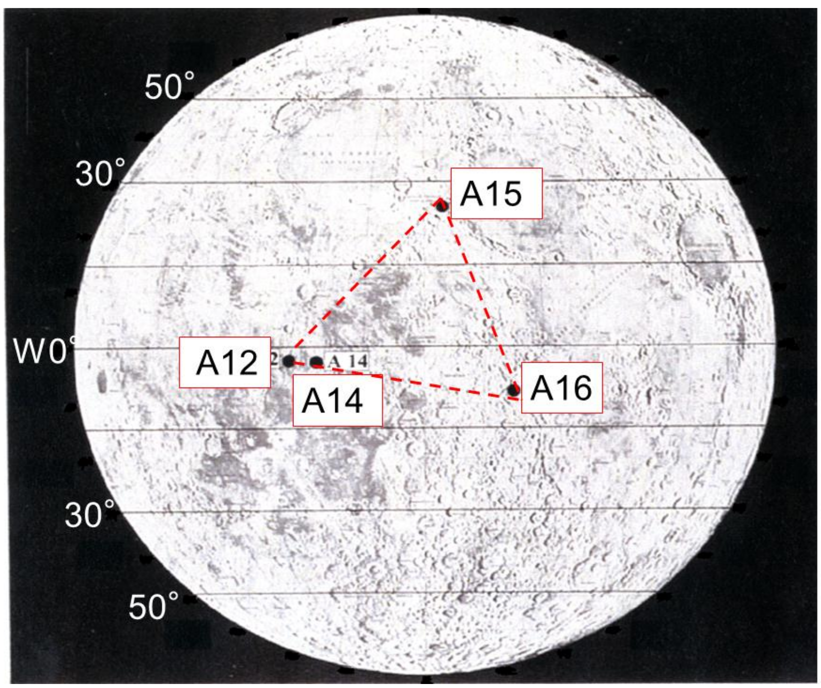

Fig.1 Apollo Passive Seismic Experiment Network
(Edited figure from reference [1])

The locations and installation dates of PSE stations are listed in below table.

Apollo Passive Seismic Station Locations

Station	Date of Deployment([2])		Coordinates ([3])		Distance from lunar module (m) ([2])
	Year	Day			
11	1969	202	0.6734N	23.4729E	16.8
12	1969	323	3.0094S	23.4246W	130
14	1971	36	3.6440S	17.4775W	178
15	1971	212	26.1341N	3.6298E	110
16	1972	112	8.9754S	15.4981E	95

Azimuth of the horizontal components and the distance and azimuth among each station are also listed.

Azimuth and Distance of Apollo Passive Seismic Network Stations [2]

Station	(*)Azimuth of horizontal		Distance and azimuths from other stations			
	+x	+y	12	14	15	16
11	0	90	-	-	-	-
12	180	270	-	181km, 276°	1188km, 226°	1187km, 276°
14	0	90	181km, 96°	-	1095km, 218°	1007km, 277°
15	0	90	1188km, 40°	1095km, 33°	-	1119km, 342°
16	334.5	64.5	1187km, 100°	1007km, 101°	1119km, 160°	-

(*)Upward ground motion produces positive-going output signal for the vertical components. The listed azimuths for the horizontal-component are the directions of ground motion that give positive-going output signal (0°= north, 90°= east, 270° = west)

[Operation Status]
(Observation term)

Observation term of PSE [4]

Station	Observation term of PSE (Year/DOY)
11	1969/202 – 1969/215 1969/231 – 1969/238
12	1969/323 – 1977/273
14	1971/036 – 1977/273
15	1971/212 – 1977/273
16	1972/112 – 1977/273

(Specification of Data Acquisition)

Specification of data acquisition ([5],[6])

Sampling rate	LP	0.15094 (sec)
	SP	0.018868(sec)
Dynamic Range	±2.499 (V)	
A/D resolution	10 (bit)	

(Apollo 11 Seismometers) [7]

The Apollo 11 seismometers functioned for 21 Earth days before the loss of command uplink capability terminated operations. During the operational period, all four seismometers of the PSE functioned nominally. Some transient signals of instrument origin were detected. Three categories of signals were also detected; (1) those produced by astronaut activities, (2) those with impulsive onset and short duration, and (3) those with emergent onset and long duration.

(Apollo 12 Seismometers) [7]

The Apollo 12 LPX and LPY components functioned normally from deployment. The LPZ component originally produced abnormal responses, but this problem was corrected 3 Earth days after deployment. Intermittently, between December 1973 and March 1974, the LPZ component showed sporadic loss of data during the lunar night. It functioned normally, however, from March 1974 until ALSEP operations terminated on September 30, 1977. The SPZ component (short-period vertical motion) failed to respond to calibration pulsed and operated at a much reduced gain, obtaining little or no valid data.

(Apollo 14 Seismometers) [7]

Since initial activation of the Apollo 14 PSE, all elements operated as planned with two exceptions. The LPZ seismometer was unstable in the flat-response mode from deployment until November 17, 1976, when the problem was rectified. The Y-axis of the gimbals leveling system responded to commands only intermittently.

The Apollo 14 ALSEP suffered several periods of loss of signal (LOS), and because there was no data storage capability in the PSE, these periods represent total data loss. The cause for the LOS is unknown. Periods of LOS are listed in below table. The periods listed do not include short intervals, when higher priorities or receiving station technical problems prevented reception of data from the ALSEP.

Apollo 14 ALSEP Operational History

Loss of Signal (LOS)	Acquisition of Signal (AOS)
	Feb. 5, 1971
Mar. 1, 1975	Mar. 5, 1975
Jan. 18, 1976	Feb. 19, 1976
Mar. 17, 1976	May. 20, 1976
June 8, 1976	June 10, 1976
Oct. 9, 1976	Nov. 12, 1976
July 30, 1977	Aug. 4, 1977

(Apollo 15 Seismometers) [7]

Since the initial activation of the Apollo 15 PSE, all elements operated as planned. The one exception was that the sensor thermal control system did not maintain designed temperature ranges. This is believed to have been caused by uneven deployment of the thermal shroud. Despite this, data return was nominal.

(Apollo 16 Seismometers) [7]

The Apollo 16 PSE was the most sensitive seismological instrument emplaced on the Moon during the Apollo program. The instrument continued the observations made by the earlier missions and served to expand the lunar seismic network.

The only problems encountered in the instrument were with the sensor thermal control system and excessive noise from the SPZ seismometer. This noise occurred at intervals that appear to have correlated with the temperature fluctuation cycle.

(LP Peaked and Flat Mode) ([5],[8])

The LP seismometer has two operational modes (Peaked and Flat Mode). On the Flat Mode, the feedback filter is turned on to accomplish the high sensitivity in the region of low frequency, although the operating in flat mode sometimes made the seismometers unstable. For the most part of ALSEP observations, the LPs were operated in peaked mode except later term of the observations in some seismic stations. In following table, the operation term in LP Flat Mode for each station is listed.

The operation term in Flat Mode response

Station	Flat Mode operation term
12	1974. Oct. 16 – 1975. Apr. 9
	1975. June. 28 – 1977. Mar. 28
14	1976. Sept. 18 – 1976. Nov. 17
15	1975. June. 28 – 1977. Mar. 28
16	1975. June. 28 – 1977. Mar. 28

[Artificial Impacts]

In early stage on PSE, nine artificial impacts were generated on the lunar surface. The impacting bodies are the Saturn third-stage booster (S4B) and the ascent stage of the lunar module (LM); the origin times and locations of the impacts are know from tracking. The locations of the artificial impacts are summarized in below table.

Locations of the artificial Impacts [9]

Impact	Coordinates		Distance and Azimuth from Apollo Seismic Stations			
			12	14	15	16
LM-12	3.94 S	21.20 W	73km, 112°	-	-	-
S4B-13	2.75 S	27.86 W	135km, 274°	-	-	-
S4B-14	8.09 S	26.02 W	172km, 207°	-	-	-
LM-14	3.42 S	19.67 W	114km, 96°	67km, 276°	-	-
S4B-15	1.51 S	11.81 W	355km, 83°	184km, 69°	-	-
LM-15	26.36 N	0.25 E	1130km, 36°	1048km, 29°	93km, 276°	-
S4B-16(*)	1.±0.7N	23.8±0.2 W	132km, 355°	243km, 308°	1099km, 231°	-
S4B-17	4.21 S	12.31 W	338km, 96°	157km, 96°	1032km, 209°	850km, 278°
LM-17	19.96 N	30.50 E	1750km, 64°	1598km, 61°	770km, 98°	985km, 27°

(*)Premature loss of tracking data reduced the accuracy of the estimate of the S4B-16 impact point. The listed coordinates for this impact are estimated from seismic data.

The impact times are also listed in below table.

Times of the Artificial Impacts [9]

Impact	Date	Time, UT(*)
LM-12	Nov. 20, 1969	22h 17m 17.7s
S4B-13	April 5, 1970	1h 9m 41.0s
S4B-14	Feb. 4, 1971	7h 40m 55.4s
LM-14	Feb. 7, 1971	0h 45m 25.7s
S4B-15	July 29, 1971	20h 58m 42.9s
LM-15	Aug. 3, 1971	3h 3m 37.0s
S4B-16	April 19, 1972	21h 2m 4±4s (†)
S4B-17	Dec. 10, 1972	20h 32m 42.3s
LM-17	Dec. 15, 1972	6h 50m 20.8s

(*)All times in this table are range times, i.e., times received on earth

(†)Estimated Value

Impact Parameters of Artificial Impacts [9]

Impact	Velocity (km/s)	Mass (kg)	Kinetic Energy (ergs)	Angle from Horizontal (deg)
LM-12	1.68	2383	3.36E+16	3.7
S4B-13	2.58	13925	4.63E+17	76
S4B-14	2.54	14016	4.52E+17	69
LM-14	1.68	2303	3.35E+16	3.6
S4B-15	2.58	13852	4.61E+17	62
LM-15	1.7	2385	3.44E+16	3.2
S4B-16	(§)	(§)	(§)	(§)
S4B-17	2.55	14487	4.71E+17	55
LM-17	1.67	2260	3.15E+16	(§)

(§) Not available

The Impact parameters, velocity, mass, kinetic energy and impact angle from horizontal, of artificial impacts are indicated in above table.

[Lunar Seismic Events]

Through Apollo passive seismic experiments, four distinct types of natural seismic source have been identified. They are deep moonquakes, shallow moonquakes, thermal moonquakes and meteoroid impacts. They reflect the present dynamic state of the lunar interior and the interplanetary environment around the Moon. I describe their characteristics briefly.

(Deep Moonquakes) ([10], [11])

These, the most abundant type, are small-magnitude events that occur at depths about halfway between the surface and the center of the Moon. Their occurrence is strongly correlated with the tides raised on the moon by the Earth and the Sun. The total number of distinct source regions identified to date is 166 [11]. The nearly identical waveforms of individual moonquakes from a given source region allow us to use a stacking technique (addition of amplitudes of many seismograms) to improve the signal-to-noise ratio of seismograms. The signal-to-noise ratio is maximized by appropriately weighting individual seismograms. The use of P and S-arrival time readings from these stacked seismograms enable us to locate the deep moonquake sources with better accuracy.

Of 166 source regions identified by distinct waveforms, 106 have been located [11]. 8 sources among these located sources willing to be located on the lunar far-side. This small number of located sources on the far-side allows us to infer the existence of a partially molten zone in the lower mantle. However, this does not rule out the possibility that deep moonquakes are absent in the far side. Most foci occur within a clearly defined region between depths of 800 km and 1000 km. This indicates that a broadly diffused zone of foci bounded below by the partially molten lower mantle.

The process that causes deep moonquakes has been a subject of considerable discussion. Several lines of evidence now suggest that these quakes are not caused by tectonic stresses in the Moon, but rather represent dissipation of tidal energy in the moon generated by the relative motions of the Earth and the Sun. Tidal stresses concentrated at certain heterogeneities in the deep lunar interior appear to cause deep moonquakes to occur there, although more detailed studies are needed to clarify the mechanism.

(Shallow Moonquakes) ([12], [13])

Shallow moonquakes are the most energetic seismic sources we observed on the moon although they are rare compared with all the other types of seismic events. This seismic event has predominant signal in high-frequency region, and it is called HFT (High Frequency Tele-seismic) events. Their occurrence is not clearly correlated with the tides as in deep moonquakes, so they are quite likely to be tectonic in origin. Most, if not all, of them occur in the upper mantle of the Moon.

Nakamura et al., (1979) [12] have shown that several characteristics of shallow moonquakes are common to those of intra-plate earthquakes. For example, both shallow moonquakes and intra-plate earthquakes appear to occur in zones of pre-existing weakness in a lithospheric plate; also the relative abundances of large and small quakes are similar, suggesting that similar mechanism generate them on both planets.

On the other hand, Frohlich and Nakamura, (2006) [13] observed that HFT event occurrence correlates with the lunar sidereal period of 27.32 days; i. e., HFT events are significantly more common when the seismic network on the front side of the Moon is oriented in a particular direction with respect to the celestial sphere. This may indicate that one exotic possibility is that the HFT moonquakes are caused or triggered by ultra-massive ultra-high-energy cosmic particles.

(Thermal Moonquakes) ([14])

These are the very small seismic disturbances caused by temperature variations at or near the surface of the Moon. They are detectable only at distances up to a few kilometers from a seismic station. The mechanism for their generation is not well understood, though they seem to originate at young craters and large rocks [14]. They probably represent thermal degradation processes acting upon relatively young lunar surface features.

(Meteoroid Impacts) ([15], [16], [17])

The origin of meteoroid impacts is clearly not internal to the Moon, and thus they do not represent true lunar seismicity. However, meteoroid impacts observed by the lunar seismometers are an important source of information on the interplanetary environment and lunar interior structure. Those meteoroids detected by the long-period seismometers have estimated masses in the range from 500 g to 50 kg [15], while the much more numerous impacts detected by short-period seismometers and the LSPE geophones represent those of smaller masses.

The seismic data clearly show that the large meteoroids are not distributed evenly in the surrounding interplanetary space, but show clustering [16]. Some of these clusters may be related to known meteor showers. (Oberst and Nakamura, 1991) [17] showed that a distinct difference between ‘small’ meteorites (masses smaller than about 1kg) and ‘large’ meteoroid (masses larger than about 1kg). Small meteoroids show strong clustering, many of which are identified with showers known from terrestrial meteor studies. In contrast, little clustering is found for large meteoroids, suggesting that they represent meteoroids of type and origin different from those of the small meteoroids. The small meteoroids appear to be mostly cometary, while large meteoroids may be derived from near-Earth asteroids and short-period comers. Further analysis of the details of the distribution of impacts should reveal more about the nature of these small bodies in interplanetary space.

An example of waveforms of deep moonquake, shallow moonquake and meteoroid impacts is shown in Figure 2.

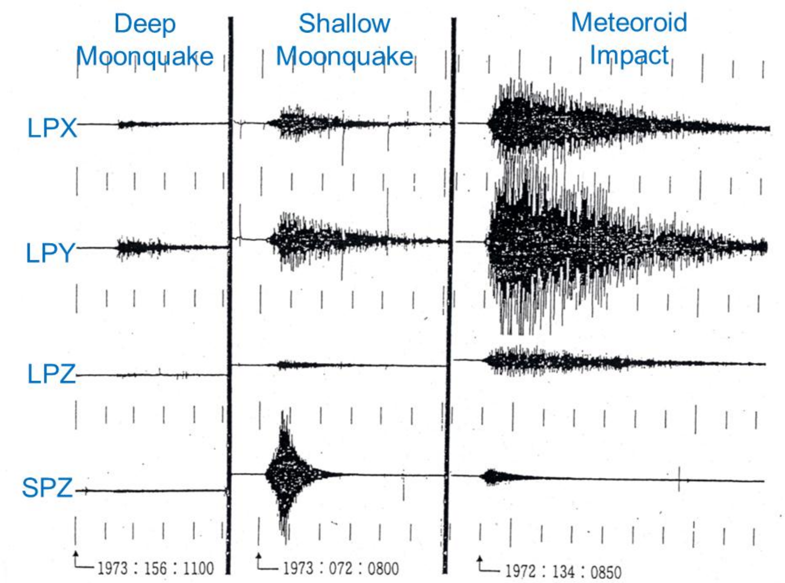

Fig.2 Representative lunar seismograms in compressed time scale. All of these are for signals of detected at the four components (LPX, LPY, LPZ and SPZ) of the seismometer on the Apollo 16 station. (Edited figure from reference [18])

(2) Active Seismic Experiments (ASE)

The Active Seismic Experiment (ASE) was part of the Apollo lunar surface experiments package (ALSEP) of the Apollo 14 and 16 missions. The purpose of the experiment was to generate and monitor seismic waves in the near lunar surface and to use these data to study the internal structure of the Moon to a depth of several hundred meters.

[ASE Sources]

The ASE data are obtained from three sources; an astronaut activated thumper, a mortar package that contains rocket-launched grenades, and the impulse produced by the lunar module (LM). Because the ascent stage of the lunar module is already described in the upper section, I'll describe the thumper and grenades.

(Astronaut Activated Thumper) ([19])

The astronaut-activated thumper is a short staff used to detonate small explosive charges-single bridge-wire 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 geo-phones and connecting cables until deployment on the lunar surface.

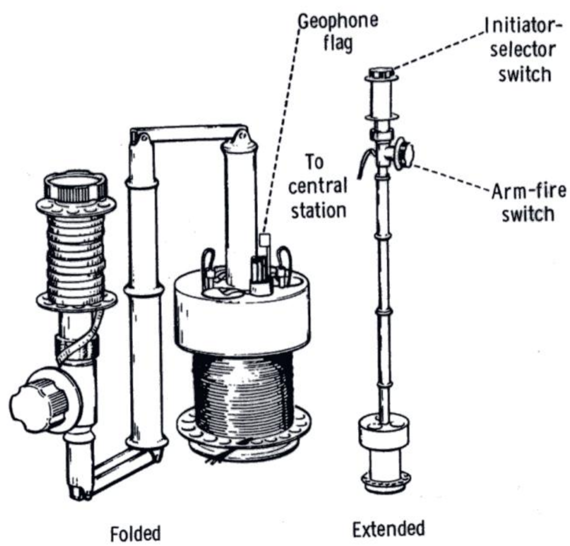

Fig.3 Schematic diagram of the thumper in the folded and extended positions [20].

(Rocket-Launched Grenade) ([19])

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

The four grenades are similar but differ in the amount of propellant and high explosive. 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 motor 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 micro-switch in the grenade.

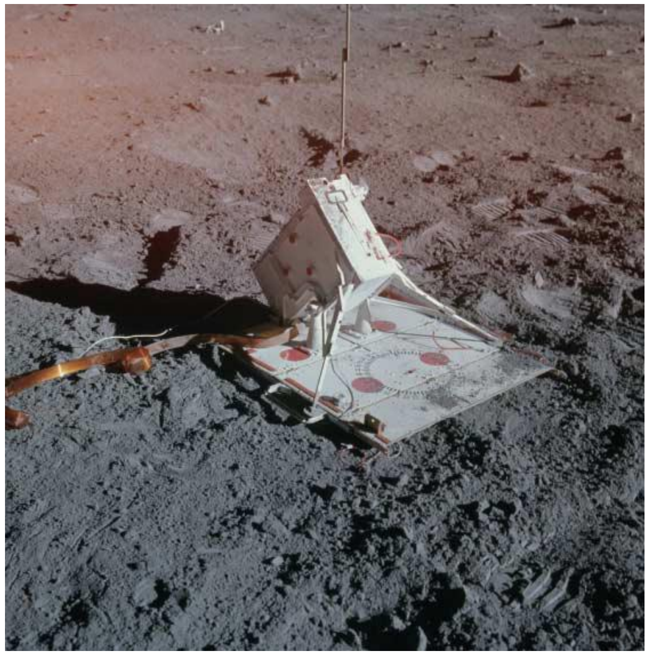

Fig.4 ASE motor containing the four rocket-propelled grenades ([20])

[Deployment of Geophones]
(Apollo 14 ASE) ([19])
At the Apollo 14 site, the three geophones are alined in a southerly direction from the ALSEP central station. 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.

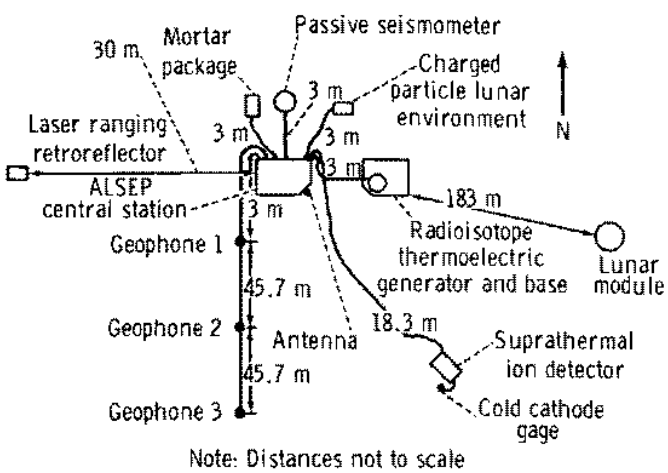

Fig.5 Deployment configuration for Apollo 14 ALSEP [21]

(Apollo 16 ASE) [22]

At the Apollo 16 site, the three geophones are aligned on a highly cratered uneven area at a bearing of 287° (clockwise from north) from the ALSEP central station. Minor difficulty was experienced in the deployment of the MPA pallet, and one of the four stakes was not implanted.

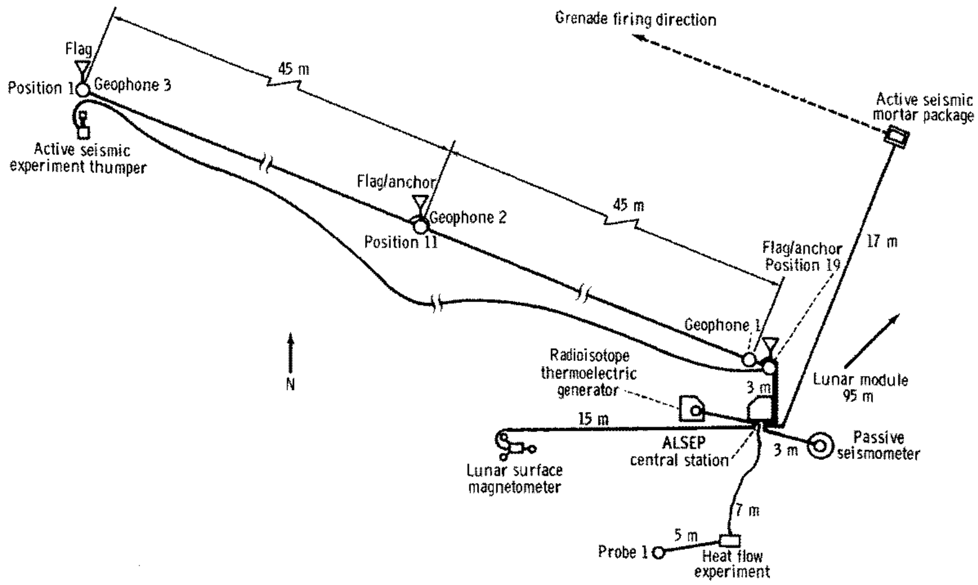

Fig.6 Deployment configuration for Apollo 16 ALSEP [21]

The MPA was leveled and armed to fire the four grenades on command to distances of 150, 300, 900 and 1500 m in a direction bearing 287° clockwise from north. The mortar mode of operation for the ASE is shown in Figure 7.

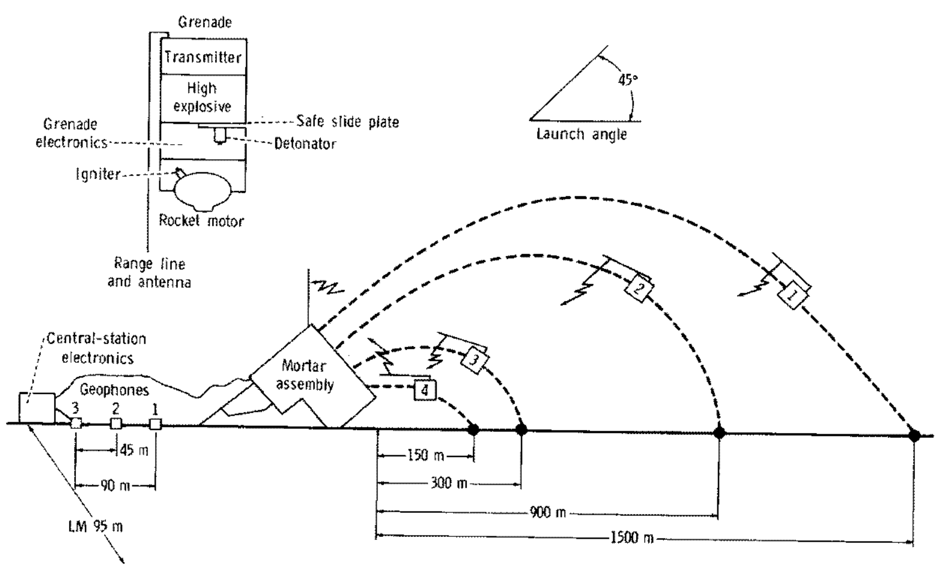

Fig.7 Schematic diagram of mortar mode operation for the ASE [22]

[Operation Status]

(Apollo 14 ASE)

①Thumper operation ([19])

Before beginning thumper operations at geophone 3, it was noted that the alignment 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, day 37, 1971 and continued until 18:37 G.m.t. Thumper firings were begun with shot1 at geophone 3 and continued at 4.6 m (15-ft) intervals along the geophone line to shot 21 at geophone 1. The thumper failed to fire after several attempts at 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 geophone2); 12, 13, 17, 18, 19, 20 and 21 (located at geophone 1). The details of the origin time and distance between each geophone and each shot are listed in 'ASE_Data_Catalog' in our retrieval system.

During thumper operations on the lunar surface, the astronaut 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. Characteristically, the seismic signals produced by thumper firing within 9 m 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.

②Motor mode operation ([23])

The Apollo 14 grenades have not been fired. A study of the deployment photographs and the astronaut's description of the motor box positioning raised the question of the back-blast effect on other experiments. A post-mission vacuum chamber test was conducted with the ALSEP configuration the same as that deployed on the lunar surface. The results of this test indicated that the back blast might damage the other experiments and the ALSEP central station; therefore, it was decided that the motors will not be fired.

(Apollo 16 ASE)

①Thumper operation ([22])

The ALSEP central station was commanded to the high-bit-rate mode at 19:54:30 G.m.t. on April 21, 1972, to record the ASE/thumper mode of operation. Thumping operation began at 20:01:52 G.m.t. at geophone 3 (farthest from the ALSEP central station) and proceeded at 4.75 m (15-ft) intervals (except between positions 11 and 12 and positions 18 and 19, which are at 9.5 m (30-ft) intervals) toward geophone 1 (nearest to the central station). The final thumper shot was fired at 20:16:08 G.m.t., which resulted in a 14-min time line. Seismic signals were recorded at all three geophones for all 19 thumper firing. The details of the origin time and distance between each geophone and each shot are also listed in 'ASE_Data_Catalog' in the data-base.

②Mortar mode operation ([23])

Three of the four grenades at the Apollo 16 site have been fired. On May 23, 1972, the Apollo 16 ALSEP was commanded to high bit rate between 5:20:00 and 6:44:00 G.m.t. for the ASE/mortar mode of operation. Three of the four high-explosive grenades in the mortar package were successfully launched in the following sequence; Grenade 2 (1024 g) was launched a distance of

900 m; Grenade 4 (695 g) was launched a distance of 150m; and Grenade 3 (775 g) was launched a distance of 300m. Grenade 1, which weighted 1261 g and was to be launched a distance of 1500 m, was not launched because the mortar package pitch angle sensor went off-scale high after grenade 3 was fired. The off-scale indication makes the pitch position of the launch assembly uncertain; therefore, the decision was made to delay launching of the mortar as long as the other Apollo 16 experiments were gathering valid scientific data. Finally, the Grenade 1 had never been fired.

(Specification of Data Acquisition)

Specification of Data acquisition of ASE ([23])

Sampling rate	530 Hz
Dynamic Range	4.094(V) (Logaritmic Compressor)
A/D resolution	5(bit)

The detail of the specification is also described in another document; [The Apollo Seismometer Responses].

[3] Lunar Seismic Profiling Experiment (LSPE)

The purpose of the Apollo 17 lunar seismic profiling experiment (LSPE) was to record the vibrations of the lunar surface as induced by eight explosive charges, by the thrust of the lunar module (LM) ascent engine, and by the crash of the LM ascent stage. Analysis of these seismic data were planned to determine the internal characteristics of the lunar crust to a depth of several kilometers. The travel times of seismic waves are inverted to determine the seismic velocity structure with depth and to provide the direct means of probing the lunar interior. A secondary objective of the LSPE was to monitor lunar seismic activity during periodic listening intervals. [24]

[LSPE sources] ([24])

The eight explosive packages are identical except for the amount of high explosive and the preset run-out time of the mechanical timers. An explosive package is activated by removing three pull pins. Removal of the first pull pin activates the SAFE/ARM slide timer, which is preset at 89.75, 90.75, 91.75, or 92.75 hr. Removal of the second pull pin releases the SAFE/ARM slide from its constrained SAFE position. Removal of the third pull pin removes a constraint on the firing pin and actives the thermal battery timer.

LSPE explosive packages are deployed as shown in Figure 9. No difficulty was experienced in the deployment of the explosive packages during the periods of extravehicular activity (EVA). The 454-g explosive package (EP-6) was deployed at station 1, and the 227-g explosive package (EP-7) was positioned on the return to the LM from station 1. Explosive packages 4, 1, and 8 were armed and placed on the lunar surface during the second EVA. During the third EVA, explosive packages 3, 5, and 2 were deployed. It was necessary to place the 1361-g explosive package (EP-5) at station 9 when it became apparent that insufficient time remained for a visit to the crater Sherlock. All the explosive packages were successfully detonated.

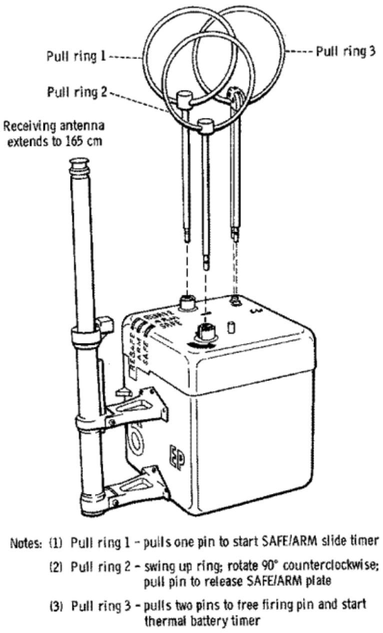

Fig.8 Schematic diagram of LSPE explosive package [24]

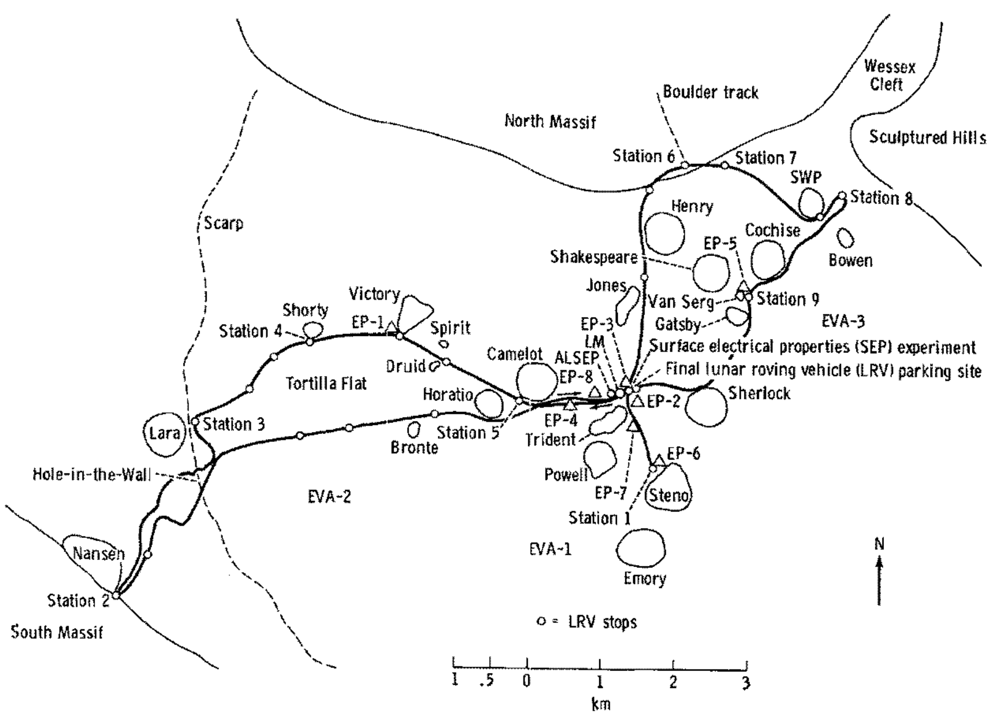

Fig. 9 Extravehicular activity traverse showing positions of deployed explosive packages at the Apollo17 landing site [24]

[Deployment of Geophones] [24]

In LSPE, four identical geophones are used in a triangular array as shown in Figure 10. The geophones are miniature seismometers of the moving coil-magnet type. The LSPE geophone array was deployed without difficulty in the nominal configuration at the Apollo 17 site approximately 148 m west-northwest of the LM.

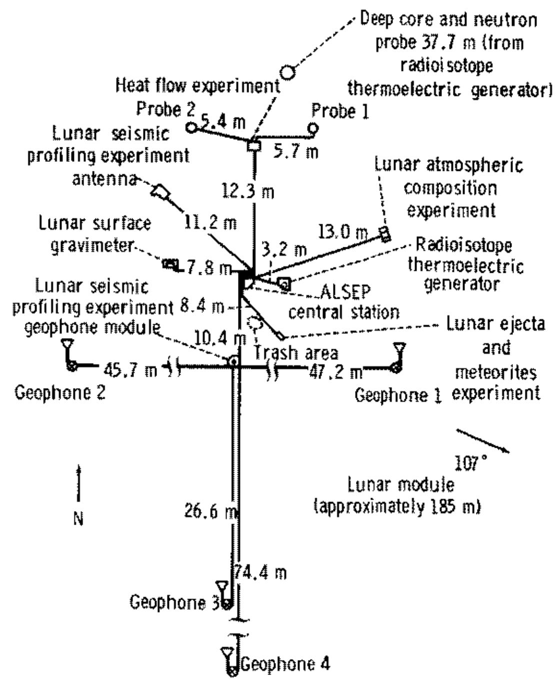

Fig.10 Deployment configuration for Apollo 17 ALSEP [21]

[Operation Status]

All eight of the explosive packages placed on the lunar surface were successfully denoted. Transmissions of the fire pulses at 29.55 sec intervals from the LSPE antenna were observable as crosstalk on the individual geophone data channels and produced convenient, accurate reference for selecting the detonation time of the individual explosive packages [24].

The locations of the explosive packages with respect to the LSPE geophone array were taken from preliminary post-mission analyses. Adjustments in the absolute distances of the explosive packages undoubtedly are necessary from analyses of the appropriate Apollo 17 lunar surface photographs [24]. Recently, Dr. Mattew Brzostowski has derived the accurate start time of each detonation and the distance between each geophone and each explosive package. This information is listed on ‘ASE_Data_Catalog’ in the database.

(Specification of Data Acquisition)

Specification of Data acquisition of LSPE ([24] & (Nakamura, 2010, personal communication))

Sampling rate	117.78 Hz
Dynamic Range	5.0(V) (Logaritmic Compressor)
A/D resolution	8(bit)

[4] Lunar Surface Gravimeter Experiment (LSG)

The LSG was deployed by the Apollo 17 crew. The primary objective of the lunar surface gravimeter (LSG) is to use the Moon as an instrumented antenna to detect gravitational wave predicted by Einstein's general relatively theory. A secondary objective is to measure tidal deformation of the Moon.

However, when the instrument was turned on, the movable beam could not be balanced by sending commands to add or subtract weights. [25]

The location and installation date of LSG at Apollo 17 station are shown in below table.

Apollo Lunar Surface Gravimeter Location

Station	Date of Deployment[26]		Coordinates [27]		Distance from lunar module (m) [21]
	Year	Day			
17	1972	347	20.19N	30.77E	~185m

[Operation Status]

(Operation Status ①) ([26])

The LSG experiment was deployed on December 12, 1972 by the Apollo 17 astronauts. The set-up procedure was to null the sensor beam by adding weights by means of a caging mechanism. However, even with both of the available masses added to the sensor beam assembly, it was not possible to balance it in the proper equilibrium position. The only time the beam moved was when the casing mechanism was in physical contact with it.

To determine if the movement of the beam was being obstructed, the Lunar Module Pilot rapped the exposed top plate on the gimbal; rocked the apparatus in several directions, re-leveled the instrument; and rechecked the tilt of the sunshade in an attempt to free the sensor beam. However, none of these actions produced any change in the operation of the instrument.

It was then determined that an error in arithmetic made by La Coste and Romberg had not been corrected by La Coste and Romberg. This led to an instrument which had excellent performance in earth G and was just barely outside of the tolerances for variations of lunar site G. This error resulted in the mass of the counterweights being about two percent less than was necessary for operation in the Moon's 1/6-g. unfortunately, the procedure of adding the weights allowed only for up to plus or minus 1.5 percent for possible inaccuracies.

Therefore, it was necessary to balance the beam using a very small force applied by the mass adding mechanism. However, this changed the frequency response of the sensor to a significantly higher frequency than that originally intended. However, the balanced beam system had a much higher quality factor about 25 instead of being critically damped. This led to much greater sensitivity than the intended design near the resonance and poor sensitivity at very low frequencies. The system was left in open loop (integrator shorted) mode. (The constitution and the characteristics of the LSG sensor can be referred from [The Apollo Seismometer Response].)

(Operation Status②) ([26])

After 45 days, no seismic signal was detected, and it was found that the sensor had deviated sufficiently from its proper equilibrium position to saturate the final amplifier. The beam was again centered, and the output observed during a terminator crossing (lunar sunrise or sunset), when rapidly changing temperature would be expected to produce enough stresses on the lunar surface to produce detectable seismic activity. Comparison with the Lunar Seismic Profile Experiment (LSPE) verified that the LSG was indeed detecting information from local seismic activity.

On April 19, 1973, the natural resonant frequency was successfully lowered to approximately 2.2 Hz, with a displacement sensitivity of 3.5 Å. The experiment was left in open loop to obtain some long term results before further experiments were attempted.

On September 26, the experiment was configured for the first time in closed loop operation, in order to detect tidal data. This also reduced the possibility of saturation, so the seismic gain was again returned to maximum. The spring constant and the beam assembly frequency response were measured.

In an attempt to further reduce the instrument's resonant frequency, another reconfiguration was performed on November 30 to better center the sensor beam with mass caging mechanism. As a result, the natural frequency was lowered to approximately 1.5 Hz, and there was noticeable improvement in the free mode channel response. The tidal output was following its predicted pattern with an unexplained distortion in the high frequency region. Unfortunately, the tidal signal later began to show a constant reading at its minimum value, indicating a hardware failure in the tidal channel. No explanation could be found for the problem, and the experiment was left on December 7 in open loop made with maximum seismic output.

The experiment continued to gather useful data until March 15, 1974, when the heating mechanism began to malfunction, making it impossible to accurately maintain stabilized operating temperature without which no useful data could be obtained. However, the heating system regained normal operation on April 20.

Summary of Operation History [28]

Days	Status
1-8	Set up and troubleshooting procedures
8-23	BEAM resting on upper stop. PA Gain = 17
23-116	BEAM centered PA Gain = 86.4 Input to high gain seismic saturated
116-129	BEAM centered PA Gain = 64 Coarse screw at upper limit
129-289	BEAM centered PA Gain = 64 Coarse screw near bottom giving 1.6 Hz resonance
289-360	Began close loop operation
360-	Began open loop operation with maximum seismic output

The 1st day means December 12, 1972.

(Specification of Data Acquisition)

Specification of Data acquisition of LSG ([28], [29])

Sampling rate	51.4 (Hz) (Seismic Mode)
Dynamic Range	±10.24 (V)
A/D resolution	10 (bit)

[Seismic Observation]

Initial analysis had been made in University of Maryland. They had indicated that the LSG did not work as gravimeter to detect gravitational wave, but it could detect some lunar seismic events. Direct comparisons of the LSG data with other seismic measuring devices on the Moon have shown it to have within a narrow bandwidth a greater degree of sensitivity. The LSG can be used as an under-damped seismometer. [26]

Recently, Kawamura et al., (2009) ([30]) have analyzed the LSG seismic data in the period from 1976/3/1 to 1977/9/30 in Work-Tape Normal-Bit-Rate. They have indicated that there were seismic event data with quality enough to analysis in the LSG record with other PSE data. Figure 11 shows a waveform of a shallow moonquake event detected by the LSG with seismic mode.

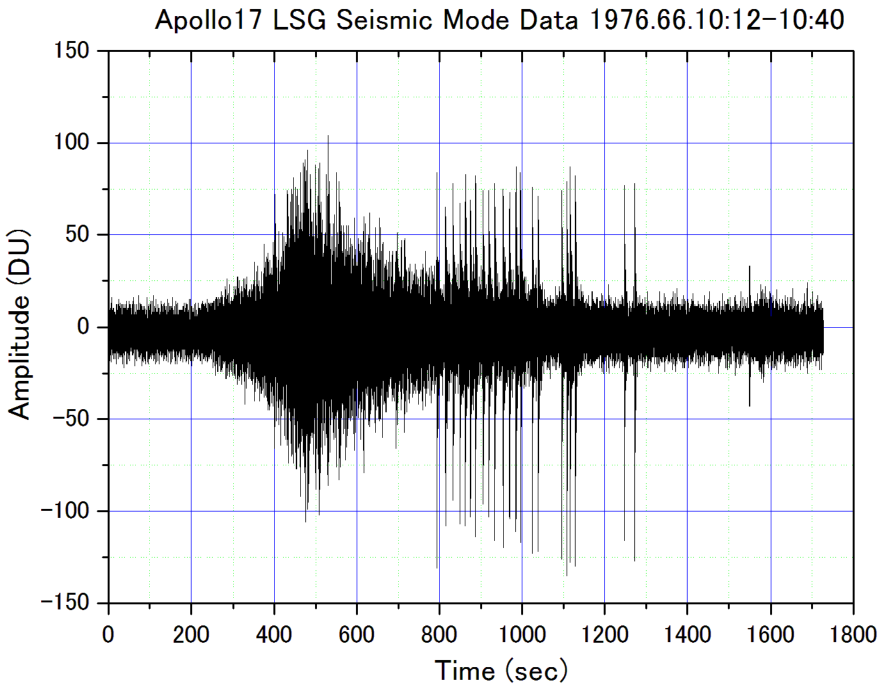

Fig. 11 A Waveform of a show moonquake event detected by LSG at 1976.66.10:12-10:40

[References]

(Apollo Passive Seismic Experiment)
[1]A. Khan and K. Mosegaard
An inquiry into the lunar interior: a nonlinear inversion of the Apollo lunar seismic data
Journal of Geophysical Research (2002) 107, E6, p.1-18

[2]LYNDON B. Johnson Space Center Memorandum
Passive Seismic Experiment (NASA Experiment S-031);
In Apollo Scientific Experiments Data Handbook
JSC-09166 (1974) pp.4-1 – 4-29

[3]M. E. Davies and T. R. Colvin
Lunar coordinates in the regions of the Apollo landers
Journal of Geophysical Research (2000) 105, E8, pp.20277-20280

[4]Y. Nakamura
Catalog of lunar seismic data from Apollo Passive Seismic Experiment on 8-mm Video Cassette (Exabyte)
UTIG Technical Report No.118 (1992)

[5]R. Bulow, C. Johnson, P. Shearer
New events discovered in the Apollo lunar seismic data
Journal of Geophysical Research (2005) vol.110, E10003, pp.1-22

[6]P. Horvath
Analysis of lunar seismic signals – Determination of instrumental parameters and seismic velocity distributions-
Doctoral thesis in the University of Texas at Dallas

[7]R. Vostreys
DATA USER'S NOTE Apollo Seismological Investigations
NSSDC/WDC-A-R&S 80-11 (1980)

[8]J. Bates, W. Lauderdale, H. Kernaghan
Operational History; in ALSEP Termination Report
NASA Reference Publication 1036 (1979) pp.4-1 – 4-47

[9]M. N. Toksoz, A. M. Dainty, S. C. Solomon, K. R. Anderson
Structure of the Moon
Reviews of Geophysics and Space Physics (1974) vol.12, No.4, p.539-565

[10]Y. Nakamura, G. Latham, H. Dorman
Apollo lunar seismic experiment –final summary
Journal of Geophysical Research (1982) 87, supplement, A117-A123

[11]Y. Nakamura
Farside deep moonquake and deep interior of the Moon
Journal of Geophysical Research (2005) 110, E1001, p.1-12

[12]Y. Nakamura, G. Latham, H. Dorman, K. Ibrahim, J. Koyama, P. Horvath
Shallow moonquakes; Depth, distribution and implications as to the present of the lunar interior
Proceeding of Lunar and Planetary Science Conference 10th (1979) p.2299-2309

[13]C. Frolich and Y. Nakamura
Possible extra-Solar-System cause for certain lunar seismic events
ICARUS (2006) 185, p.21-28

[14]F. Duennebier
Thermal movement of the regolith
Proceeding of Lunar and Planetary Science Conference 7th (1976) p.1073-1086

[15]F. Duennebier, J. Dorman, D. Lammlein, G. Latham, Y. Nakamura
Meteoroid flux from passive seismic experiment data
Proceeding of Lunar and Planetary Science Conference 6th (1975) p.2417-2426

[16]F. Duennebier, Y. Nakamura, G. Latham, H. Dorman
Meteoroid storm detected on the Moon
Science (1976) 192, p.1000-1002

[17]J. Oberst, Y. Nakamura
A search for clustering among the meteoroid impacts detected by the Apollo lunar seismic network
Icarus (1991) 91, p.315-325

[18]Y. Nakamura
Seismology on the Moon (In Japanese)
科学 (1976) 46, No.3, p.135-144

(Apollo Active Seismic Experiment and Lunar Seismic Profiling Experiment)
[19]R. Kovach, J. Watkins, T. Landers
Active Seismic Experiment; in Apollo 14 Preliminary Science Report
NASA SP-272 (1971) p.163-174

[20]M. Brzostowski and A. Brzostowski
Archiving the Apollo active seismic data
The Leading Edge (2009) p.414-416

[21]J. Bates, W. Lauderdale, H. Kernaghan

Introduction in ALSEP Termination Report
NASA Reference Publication 1036 (1979) pp.1-1 – 1-7

[22]R. Kovach, J. Watkins, P. Talwani
Active Seismic Experiment; in Apollo 16 Preliminary Science Report
NASA SP-315 (1972) p.10-1 – 10-14

[23]Active Seismic Experiment (NASA Experiment S-033)
In Apollo Scientific Experiments Data Handbook, NASA TM X-58131
JSC-09166 (1974) p.5-1 – 5-25

[24]R. Kovach, J. Watkins, P. Talwani
Lunar Seismic Profiling Experiment; in Apollo 17 Preliminary Science Report
NASA SP-330 (1973) p.10-1 – 10-12

(Apollo Lunar Surface Gravimeter)
[25]J. Giganti, J. Larson, J. Richard, J. Weber
Lunar Surface Gravimeter Experiment; in Apollo 17 Preliminary Science Report
NASA SP-330 (1973) p.12-1 – 12-4

[26]J. Giganti, J. Larson, J. Richard, R. Tobins, J. Weber
Lunar Surface Gravimeter Experiment Final Report
Contract NASA 9-5886 (1977) p.1-21

[27]D. R. Williams
Apollo17; in The Apollo program (1963-1972)
http://nssdc.gsfc.nasa.gov/planetary/lunar/apollo17info.html

[28]J. Weber, J. Larson
Lunar Surface Gravimeter Experiment (LSGE)
Report in Physics Department of University of Maryland

[29]Lockheed Electronics Company Inc
Apollo lunar surface experiment package archive tape description document
Contract NAS 9-12200, JSC-09652

[30]T. Kawamura, S. Tanaka, Y. Saito, Y. Kobayashi, K. Horai, A. Hagermann
Re-determination of deep moonquake sources using the Apollo 17 lunar surface gravimeter
Abstract of 40th Lunar and Planetary Science Conference (2009) #1653