Detection of the Lunar Deep Moonquake at Apollo 17 Site

Yasuyuki Saito[1,2], Shota Ono[1,2], Taichi Kawamura[1,2], Satoshi Tanaka[2], Yoshio Nakamura[3], Axel Hagermann[4], Ki-iti Horai[2]

[1] *The University of Tokyo, Graduate School of Science*
[2] *The Japan Aerospace Exploration Agency*
[3] *The Texas University* [4] *The Open University*

Abstract

Lunar earthquake called Moonquake had been observed by Apollo missions. This experiment was carried out in a part of the ALSEP (Apollo Lunar Surface Experiments Package) of Apollo 12, 14, 15, and 16. Network observation using all of the stations was carried out for about five years until September 30, 1977. On the other hands, the Lunar Surface Gravimeter (LSG) experiment was carried out in Apollo 17 mission in order to detect gravitational waves and measure tidal deformations of the Moon. This experiment has never obtained meaningful data for gravity, however, the instrument had been functioned as a seismometer. In this study, we examined the LSG data and confirmed that it was detecting seismic signals by using band-pass filter and spectrogram. These analyses enabled us to improve the accuracy of determination of arrival times. The error of the arrival times of deep moonquakes are expected to be about 30 seconds. The analysis of the LSG data as a seismometer expands the observable area of Apollo seismic observation network. With the expanded network, we may be able to determine seismic centers of unclassified deep moonquakes. If seismic centers of the far side of the Moon can be identified, the observed signals may have passed the lunar core. We are expecting to obtain some new information of the lunar interior from the analysis of the LSG data.

1 Introduction

The network observation of seismic signals was carried out on the moon. Because the seismic data provides the most direct method to estimate the layer structure such as the crust and mantle, an accurate determination of the thickness and elastic wave velocity of each layer are essential for a better understanding of the origin and evolution of the Moon.

Lunar earthquake (called Moonquake) had been observed during the Apollo missions. These experiments were carried out as a part of ALSEP (Apollo Lunar Surface Experiments Package) of Apollo 12 to 16 except for Apollo 13 mission for about eight years between November 19, 1969 and September 30, 1977 (Bates *et al.,* 1979[1]). Apollo stations 12, 14, 15 and 16 were placed in an approximate equilateral triangle with distance between corners being about 1100 km and two of them, Apollo 12 and 14, were placed only 180 km apart in one corner. This triangle has been called the triangle network of Apollo seismic measurement. In the 8-year period, 12,558 events were recorded (see Table 1). These events were found to differ in signal characteristics and were grouped into four categories: deep moonquake, shallow moonquake, meteoroid impacts and thermal moonquake (Toksoz *et al.,* 1974[15]; Nakamura, 1982[9]; Nakamura, 2003[10]).

Table 1: Cataloged seismic events

Type	Number of events
Artificial impact	9
Meteoroid impact	1,743
Shallow moonquakes	28
Deep Moonquake	7,245
Unclassified	3,533
Total	12,558

Nakamura *et al.,* 1981[11]; Nakamura, 2003[10]

Apollo seismic data provides us detailed information of the lunar interior. Some studies showed that the seismic discontinuities were found at about 60 km and 500 km in depth (Nakamura, 1982[9], Goins *et al.,* 1981[4], Lognonne *et al.,* 2003[8], and Khan *et al.,* 2000[5]). It has been interpreted that these discontinuity is boundary between crust and mantle, and upper and lower mantle, respectively. It means that the Moon is a differentiated body, which implies that it experienced hot era and has a metallic core.

Since limited depth distribution of the deep moonquakes and the absence of identifiable moonquake on the hemisphere opposite to that of the triangle network, seismic velocity information was precluded being inferred below a depth of about 1150 km. A lot of measurement was carried out in order to estimate that there is metallic core in the Moon, for example mass and moments of inertia, induced dipole moment, lunar laser ranging, and so on. These measurements indicate that the

[1]saito@planeta.sci.isas.jaxa.jp

Moon has partially molten region within deeper than about 500 km in radius. If there is a seismometer at Apollo 17 landing station site, there is a possibility that we find opposite deep moonquake and direct evidence of a lunar core.

The seismic experiment had never been carried out at Apollo 17 landing site. On the other hands, the Lunar Surface Gravimeter (LSG) experiment had been done. The LSG was set in order to detect gravitational waves and to measure tidal deformations of the Moon. Unfortunately, this experiment failed and it was concluded that no provision has been made to supply data from this experiment[7]. However, as a result of our study (Saito *et al.,* 2007[13], Ono *et al.,* 2007[12]), we succeeded in archiving the Lost Apollo data and the LSG data was included in the data set.

In this study, we report the result of performance assessment of the LSG, and show that deep moonquake signal obtained by the LSG can be used in seismic analyses in order to accomplish the ultimate objective; revealing that if there is a core in the Moon or not.

2 Lunar Surface Gravimeter Experiment

The primary objective of the LSG was to use the Moon as an instrumented antenna to detect gravitational waves predicted by Einstein's general relativity theory[3]. If gravitational waves of sufficiently high intensity covering certain bands of frequencies are incident on the Moon, internal vibrations of the Moon will be excited. These vibrations may cause oscillatory surface accelerations[3]. Approximate estimates suggest that present procedure have a fair chance of observing real effects by using the Moon because of the relative quiet of the lunar environment. In addition, the LSG was also designed to measure the tidal effects on the Moon and to serve as a one-axis seismometer with seismic mode[16]. Thus, the LSG had three bands: tide, free, and seismic mode. Tide mode covers the frequency range from 0 to 0.048 Hz, free mode covers the range from 0.00083 to 0.048 Hz, and seismic mode covers the range from 0.05 to 16[16].

A schematic diagram of the spring-mass suspension system is shown in Figure 1. The LSG used the Lacoste-Romberg type of spring-mass suspension to sense changes in the vertical component of local gravity. This instrument is a sensitive balance with a mass, spring, and lever system and with electronics for observation of accelerations in the frequency range from 0 to 16 Hz. A zero-length spring is one in which the restoring force is directly proportional to the spring length; such a spring is very useful in obtaining a long-period sensor.

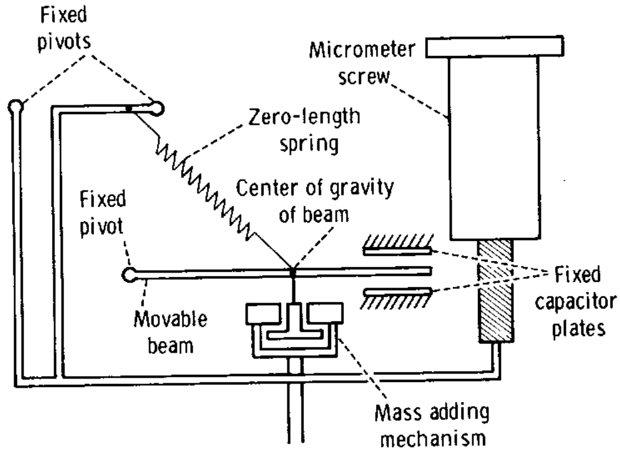

Figure 1: Schematic diagram of the Lunar Surface Gravity sensor. The beam balance between two fixed capacitor plates. The LSG employed the type of Lacoste-Romberg gravimeter. This type of gravimeter has high sensitivity for a long-period vibration phenomenon. Figure from Giganti et al. (1973)[3].

When the LSG was emplaced, it was impossible to balance the beam by sending commands to add or subtract mass because 1/6-g mass weights were too light[1]. However, as a result of reconfiguration, beam was centered and the instrument was apparently behaving like a gravimeter with resonance at 1.5Hz and possibly at a much lower frequency. In addition, the seismic data output during a several minute period associated with lunar sunrise is shown in Apollo 17 preliminary report[3]. This suggests that the instrument functioned as observation equipment for gravimeter and seismometer.

Finally, Lauderdale and Eichelman (1979) concluded that no provision has been made to supply data from this experiment because they could not find out the event signals of gravitational wave with the LSG[7] and no one could do until now, too. Many people have believed that the LSG experiment failed. Thus, the LSG have never been analyzed as seismic data in detail. Here, we show the results of the LSG data evaluation as seismic data.

3 Evaluation of the LSG data as seismic data

3.1 The LSG data in the seismic channel and its sensitivity

The LSG data was contained by six parameters in 36 ALSEP main frame words; 31 samples of seismic data, 1 sample of tidal data, 1 sample of free mode data and 2 status and 2 housekeeping words per ALSEP main frame[14]. Each ALSEP data record is 5,776 bytes and it has 60 data parts which size is 96 bytes. A data part contains 64 ALSEP words and each ALSEP word is a 10-bit word. At 1060 bps normal data rate, the nominal duration of a logical record is 10x64/1060 = 603.77 ms. The seismic channel is contained in 31 words in 603.77 ms, the sampling rate of seismic data was 603.77/31 = 19.5 ms.

Figure 2 shows the response curve of the seismic mode of the LSG copied from Giganti et al. (1977)[2]. The LSG was designed to perform with high response around 0.05Hz to 16 Hz. However, the reconfiguration had to be carried out because of the malfunction of the beam discussed previously. Eventually, the beam was recentered and the LSG carried out the observation with the response shown in Figure 2[2]. The figure shows that the response of the LSG was kept high in frequency range from 1Hz to 16 Hz with a peak around 1Hz to 2Hz. Since the lunar seismic signals are known to have characteristic peaks around 1Hz and 10Hz, the observation of the seismic mode is likely to have detected seismic signals.

3.2 Signal-to-Noise (S/N) ratio

Background noise levels of the LSG data is higher than those indicated for the Moon by the Passive Seismic Experiment and for Taurus-Littrow by the Lunar Seismic Profiling Experiment. J. Weber dealt with noisy seismic data by filtering of free-mode data by smoothing the power spectrum through stacking multi data records and averaging out noise. Since our objective is to prove that the LSG data is useful for analysis of deep moonquake with certainty, we compared the seismic signal with background noise by using the catalog of lunar seismic data[11].

Deep moonquake has characteristic frequency near 1 Hz (0.4–2 Hz). Figure 3 shows that the comparison of the background noise with deep

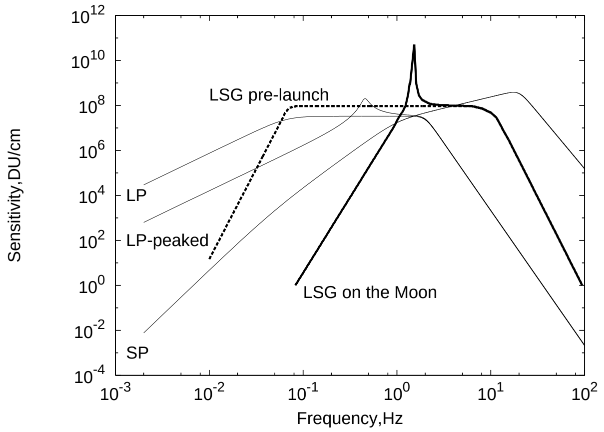

Figure 2: Response curve of the seismic mode of the LSG . The solid line indicates the response of the LSG on the Moon and the dotted line indicates that of pre-launch. The response curves of other Apollo seismographs are superposed for comparison. For Apollo seismographs SP means Short Period mode and LP means Long Period mode, which has flat mode and peaked mode. The LSG has high response comparable to other seismographs from 1Hz to 16Hz. The response curve of the LSG was cited from Giganti et al. (1977)[2], and that of other Apollo seismographs are cited from Latham et al. (1972)[6].

moonquake signal detected on March 9th, 1976 in frequency field by using Discrete Fourier Transform (DFT). Nakamura *et al.* (1981)[11] identified this deep moonquake as A7 group. Figure 3 shows that S/N ratio of this seismic event is higher than 3 at about 1.6 Hz. It implies that noise reduction using band-pass filter around this frequency may be effective.

Not all deep moonquake signal level are always larger than noise, we succeeded in detecting the deep moonquake signals of A1, A6, A7, A22 group with ratio higher than 40%. We could find out only one deep moonquake signal for A1 group. This may be because of the long distance between Apollo 17 site and A1 site. For group site other than A1 group, about 64% of the deep moonquake signals have S/N ratio higher than 2.

Figure 4 shows the comparison of the raw data with band-pass filtered signal. Seismic signals of frequency from 1.4Hz to 1.7Hz was selected. The envelope of filtered seismic signal is clearer than the one of non-filtered signal. Nakamura (1992)[9] showed that the deep moonquake (occurred on March 9th, 1976) arrived at the nearest station at AM 3:10[11]. Since the location of the A7 site is closer to Apollo 17 site compared to other seismic stations, the arrival time is likely to be earlier than AM 3:10. This seems to be consistent with the signal observed with the LSG, whose arrival

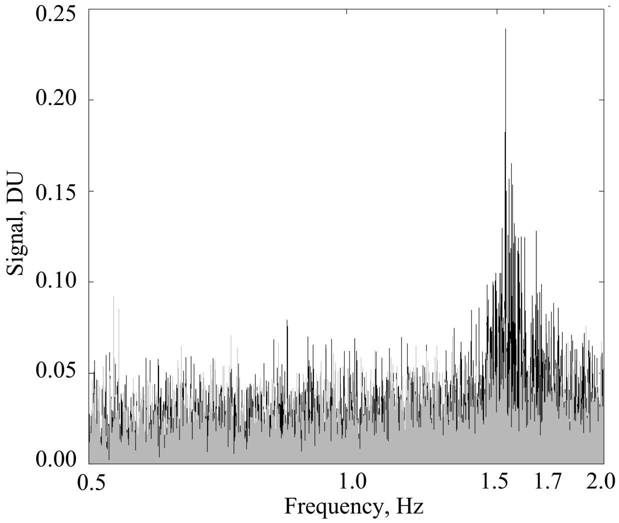

Figure 3: Characteristics frequency of A7 group deep moonquake between 0.5 Hz and 2 Hz. The gray region shows the background noise and the black region shows the seismic signal, respectively. We can see a prominent signal around 1.6Hz. Since this frequency is not dependent of the group or time, it may be occurred by characteristic of the instrument.

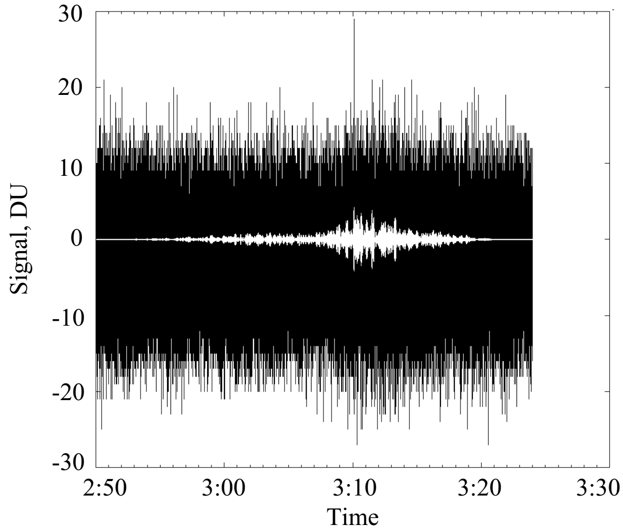

Figure 4: The comparison of the raw data (black) with band-pass filtered signal (white) by using the frequency between 1.4 and 1.7 Hz. The envelope of the seismic signal is much clearer than raw data. The figure shows that the LSG detected certain signal around 3:09. There is no signal at both ends of the filtered signal because of the effect of the window function.

time read from the filtered signal is expected to be around 3:09 or earlier. This implies that band-pass filtering is effective for improving the accuracy of determination of arrival times.

3.3 Spectrogram

In the previous section, we showed that the LSG had S/N ratio high enough to read arrival time by using the DFT technique. If seismic signal has characteristic frequency, it is likely that we can observe some kind of change in spectrum typical to seismic events. A change in frequency with time can be well understood by using a spectrogram. First, a certain time is determined as a reference, a constant time period is extracted and run the DFT. A constant time period is determined by requested accuracy of resolution in time and frequency. At least 10 seconds data need to be extracted for identification of 0.1 Hz resolution in frequency. Figure 5 shows the spectrogram of A7 group on March 9th, 1976. Data of 30 seconds was used in the DFT and this value is proportional to the time resolution of the spectrogram. The seismic signal clearly detected near 1.5 Hz between about 3:09 and 3:25. At least, it is may be able to read the arrival time to an accuracy of 30 seconds. As shown in figure 5, spectrogram is constructive for detecting small deep moonquake signal, however, there is not high resolution in time field. Then, we have to develop another method to determine the arrival time.

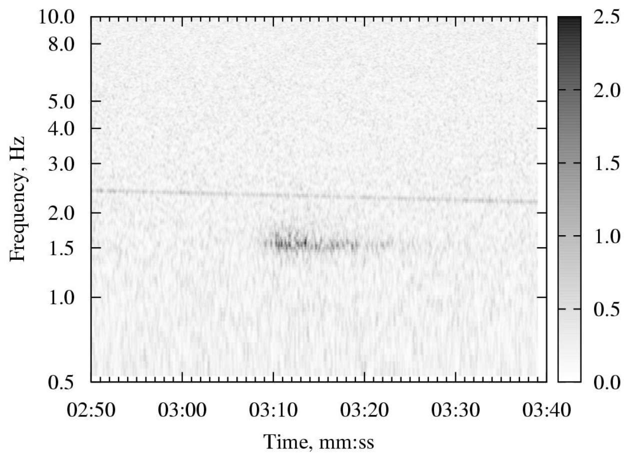

Figure 5: Spectrogram constructed from the seismic signal of the deep moonquake on March 9th, 1976.. This Moonquake is expected to be around 3:08 - 3:09, and carry on until about 3:25. Data of 30 seconds was used in the DFT to make the spectrogram.

4 Discussion

Observations of more than three seismic stations are needed to determine the seismic source of a seismic event. Since Apollo 12 site and Apollo 14 site are relatively close in the global observation network, and the number of the seismic stations is limited, the observable area of the network was restricted. In addition, all of the stations are located at the near side of the moon. Therefore, to detect the seismic event from the farside, the signal has to be relatively strong. These made the determination of seismic centers at the opposite side of the observation network difficult. Figure 6 shows the projection to equatorial plane of seismic source of deep moonquakes identified by Nakamura *et al.* (1981)[11] and Nakamura (2003)[10]. Most of these are located at the near side and 8 out of 77 deep moonquakes' seismic sources are identified as 'opposite deep moonquakes'. By adding the LSG to the observation network, the observable area expanded and detection of more 'opposite deep moonquakes' may be possible. In the figure, the tangential line from Station 12 and Station 15 to the central region with radius 300 km is drawn. This central region represents a hypothetical sphere lunar core, and seismic signals from the region more to the far side than the tangential line have a possibility of passing the lunar core. Therefore, if a seismic event occurred at the region between the two lines, which is 150 ± 15 degrees in longitude, signal through the lunar core may be detected at Station 12 or 14 while signal that did not pass the lunar core may be detected at Station 15 to 17. If we can determine the seismic source in that region, we may be able to obtain information of the lunar core from the signals observed at Station 12 and 14.

Assuming that the core-passing signal is observed at Station 12 and 14 while signal that did not pass the core is observed at Station 15 to 17 for a seismic event. By comparing the amplitude of the two types of signals, we can speculate the state of the lunar core. Heavily attenuated core-passing signals implies viscous, or may be partially molten core and vise versa. If we can distinguish P-wave from S-wave, we can obtain further implication of the lunar core. Strong P-wave and attenuated S-wave may imply a molten core.

5 Conclusion

It was believed that the LSG was unable to perform meaningful observations, however, the series of reconfigurations made it possible. The response of the LSG implied that it functioned as a seismograph and we succeeded in proving this. We also showed that the arrival time of deep moonquakes are expected to be read within error 30 seconds. Assuming that the velocity of P-wave in the mantle is 9 km/s, this error corresponds to an error of 270 km for determinations of seismic sources. This enables us to judge whether a seismic source

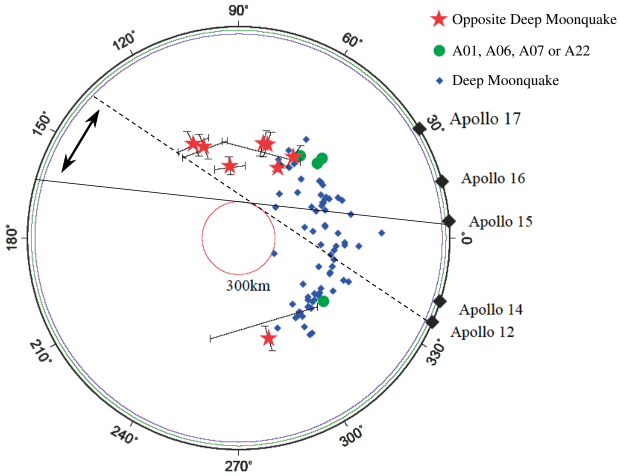

Figure 6: Projection on the equatorial plane of the seismic source of deep moonquakes identified in Nakamura *et al.* (1981)[11] and Nakamura (2003)[9]. The eight stars means opposite seismic centers, four circles means the analyzed seismic group by this study, and the others. Two lines drawn in this figure represent tangential line drawn to the central area of 300 km in radius; the solid line indicates the tangential line from Apollo 15 Station and the dotted line indicates that from Apollo 12. .

is at the near side or far side. We have already confirmed that the LSG detected the signal from A33 site, which is the seismic source farthest from the near side among the reported seismic sources of deep moonquakes. This implies a possibility that the LSG was detecting seismic signals from the region opposite to Station 12 or 14. Within these seismic signals from the far side, there may be signals that passed through the central region of the Moon. If we can detect this kind of signals, discussion on the lunar core will be possible. We are expecting to obtain new information of the lunar interior from further analyses.

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