RE-DETERMINATION OF DEEP MOONQUAKE SOURCES USING THE APOLLO 17 LUNAR SURFACE GRAVIMETER.

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Introduction: The internal structure of the Moon is essential information that infers the origin and evolution of the Moon. Many attempts have been made for its estimation and seismic analysis using the data from the Apollo Passive Seismic Experiment (PSE) is one of the most successful methods carried out. We have been focusing on the possibility of applying the Lunar Surface Gravities (LSG) data of Apollo 17 to seismological investigation [1]. Through analyses of intensive lunar seismic events called HFTs, we showed that with appropriate data processing, the data can be used in seismic analyses [2]. In this study we focused on deep moonquakes which play important role in estimating the deep inner structure of the Moon.

Deep Moonquakes: Sources of deep moonquakes are said to distribute around 1000 km in depth and occur periodically at specific source regions [3]. From the Apollo PSE data set, 7245 deep moonquakes and 166 source regions (excluding source regions that provide data only from a single station) have been reported [4]. By using the LSG as the additional seismic station, source determination with better condition will be possible. With the expanded observation network and data set, more accurate source determination will be expected. In addition, we may locate the deep moonquakes that could not be located with data set of 4 seismic stations. Among the reported deep moonquakes, 60 source regions did not provide a number of arrival time picks suffient to locate their source and their determination may impose new constraints on lunar seismology.

In this study, we try to determine source regions of deep moonquakes of various signals to noise ratio. We compare our result with previous determinations and evaluate the contribution of the LSG data to the seismic analysis of deep moonquakes.

Date Selection: As the first step, we examined two source regions that are relatively active and are near the LSG; A06 and A07. We also selected A33 as a typical farside deep moonquake to test the possibility of seismic analysis of farside deep moonquake with the LSG. Finally, we examined unlocated deep moonquakes. We chose source regions that are reported to be likely on the lunar farside in Nakamura (2005) [4]. All the analyses were done using the events in LSG data included in ALSEP 24-Hour Work Tape Files [5]. This is the only LSG data available so far and it covers observation period from 1976 3/1 to 1977 9/30.

Calculation of the Cross-correlation Coefficient and Stacking of the waveform: Since deep moonquakes occur at specific source regions, seismic signals from the same source have almost identical waveforms. Therefore, classification of deep moonquakes with their source regions will be possible by calculating the waveform cross-correlation [6]. Seismic signals classified into same source regions were then stacked in order to improve the signal to noise ratio for better arrival time readings. We applied this series of data processing to the LSG data and examined whether it is effective to the data which has poor signal to noise ratio compared to other seismic data obtained in PSE.

Result: Cross-correlation coefficient for three combinations (signals same source, signals from different source, signal and noise) was calculated and only the combination of signals from the same source showed a clear peak with high cross-correlation coefficient. With signals from same source the cross-correlation coefficient was as high as 0.8 at the peak while with other combinations, it was about 0.3 at most. Also stacked waveform calculated subsequently succeeded in improving the signal to noise ratio (Fig. 1). This shows that the calculation of the cross-correlation coefficient and stacking of the waveform can be used as an effective tool in seismic analysis of deep moonquakes with the LSG data. Therefore, further analysis was attempted with both stacked and non-stacked waveform.

For the source regions A06 and A07, with relatively good signal to noise ratio, determination with a single event using non-stacked waveform was possible. Among 13 events (8 A06 and 5 A07 events) that was detected by the LSG 10 event showed the result that support the previous determination (Fig. 2). 3 events (1 A06 and 2 A07 events) showed rather different result but this seems to be due to the error of arrival time reading since the cross-correlation coefficient show that these events are from A06 and A07 region respectively. For A07, determination using a stacked waveform was also carried out and the calculation supported the previous results. For A33, it was difficult to determine the source region with a non-stacked waveform because of the poor signal to noise ratio. Thus, only the determination with stacked waveform was done and the calculation supports the previous determination that the A33 is a farside deep moonquake. For unlocated deep moonquakes, events with signal to noise ratio enough for arrival time reading have not been found yet. 46 events were examined so far and 8 events are detected by the LSG but none of them can be used in source determination at this point.

Summary: We carried out the first seismic analysis of deep moonquakes using the LSG. We confirmed that the waveform cross-correlation and stacking are useful for classification of deep moonquakes and improving the signal to noise ratio in analyses using the LSG data. With the determination of the seismic source, all the source regions examined so far supported the previous estimations. Unlocated deep moonquakes were also examined but events with sufficient signal to noise ratio for source determination have not been found yet. However, only 17 out of 60 unlocated source regions are examined so far and there is a good chance that the remaining nests provide sufficient signals.

References: [1] Kawamura T. et al., (2008) The Lunar Surface Gravimeter as a Lunar Seismograph, *Proc. Lunar. Planet. Sci. Conf.39th 2054.* [2] Kawamura,T. et al., (2008) Re-analysis of HFT data using the Lunar Surface Gravimeter data, *Proc. Lunar. Planet. Sci. Conf.39th 2069.* [3] Lammlein, D. V. et al., (1974), Lunar Seismicity, Structure, and Tectonics., *Rev. Geophys. Space Phys. 12*, 1-21. [4] Nakamura, Y. (2005), Farside deep moonquake and deep interior of the Moon. *J. Geophys, Res.*, *110*, E01001, doi:10.1029/2004JE002332. [5] Nakamura, Y. et al., *Passive Seismic Experiment Long-Period Event Catalog, Final Version*. (University of Texas Institute for Geophysics Technical Report 18, Galveston, 1981 revised 2004) [6] Nakamura, Y. (2003), New identification of deep moonquakes in the Apollo lunar seismic data. *Phys. Earth. Planet. Inter.*, *139*, 197-205.

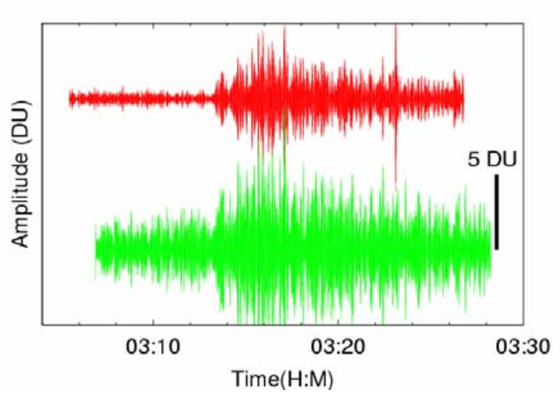

Fig. 1 Comparison of stacked waveform with non-stack waveform observed with the LSG. The upper seismogram shows the stacked waveform of A07 deep moonquake and the seismogram at the bottom shows the non-stacked waveform with best signal to noise ratio (1976 7/2 A07). The x-axis and y-axis represent the time and amplitude respectively. Clear improvement of signal to noise ratio can be seen and this implies that the waveform stacking is effective to the LSG data as well as other Apollo seismic data.

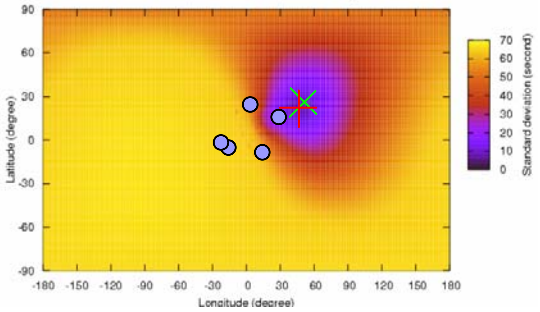

Fig. 2 Epicenter of A07 deep moonquake calculated with data from 5 seismic stations including the LSG. The circle indicates the Apollo stations. The cross and the X represent the epicenter calculated in this study and the previous study (Nakamura, 2005) respectively. Our calculation with the LSG is shown with a cross and it supports the previous source region. Similar results are also obtained with other events and these imply the possibility of the use of the LSG in seismic analysis of deep moonquakes.