Evaluation of Observation bias of Apollo Seismic Observation Network.

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Introduction: Seismic network that has been established on the Moon by the Apollo Passive Seismic Experiment has been the only example of an extraterrestrial seismic network. The network consisted of 4 seismic stations on the lunar nearside and the 4 stations formed almost equilateral triangle network with the Station 12 and 14 at one corner. Each observation site was about 1100 km apart. Since its deployment, it has provided various data and has greatly contributed to lunar seismology and lunar science(e.g. [1][2]). At the same time, the network suffered from the small number of seismic stations and the limited coverage. It has been pointed out that the observation bias of the network makes it difficult to investigate the source distribution of deep moonquakes[3]. In this study, we will try to evaluate the observation bias quantitatively and discuss weather the source distribution of the deep moonquakes we see today represents the actual source distribution.

Deep Moonquake Distribution: Deep moonquakes are most frequently observed seismic events on the Moon. Their source depths are about 900 km and are reported to occur periodically at certain source regions. About 7000 events were reported during the Apollo observation and 166 source regions, or deep moonquake nests, were reported[3].Figure 1 shows that the spatial distribution of known deep moonquake nests. Lammlein et al. [4] discuss that there is a southwest to northeast belt in the distribution of the deep moonquake nests and points out that such feature might represent some tectonic feature inside the Moon. On the contrary, Nakamura [3] claims that spatial distribution of the deep moonquake nests is not a representative one because of the observation bias of the seismic network. For most of the deep moonquake events, the magnitude is small and they cannot be detected globally. This implies that there is a good chance that we are missing some deep moonquake nests since they are either too far from the network or too weak to be detected with the network. As Lammlein et al. [4] discusses, the spatial distribution of the deep moonquakes may be related to the tectonic feature inside the Moon.

Methods: The detectability of the network depends on the sensitivity of each seismometer and geometric configuration of the network. For a given seismic event with certain magnitude and the location, we can judge whether this event is detectable at a seismic station by evaluating the signal and the noise level at the station. If we apply this to all seismic stations, we can estimate how many stations can detect the seismic event. Since we need at least 4 arrival time readings to estimate the unknowns of the seismic source, an event is preferred to be detected at 4 stations or more. On the contrary, if an event is detected only with 3 stations or less, we can say that the event is likely to be unlocated or poorly located. S/N ratio is expected to vary with epicentral distance. While signal amplitude can be estimated from attenuation model and geometrical spreading and varies with epicentral distance, the noise level is expected to be independent of the epicentral distance. Using such relation, we can express the variation of S/N ratio with epicentral distance. Then we will express the reading error as a function of S/N ratio. This was done by examining the reading error that was obtained from the actual arrival time reading and we estimated an empirical relation between S/N ratio and arrival time reading error. Using the two relations, we will have an empirical relation between epicentral distance and the arrival time reading errors. This will enable us to evaluate the data quality of a deep moonquake of a given location and a given magnitude observed at a given station. The estimation of the data quality also enables us to evaluate the location error of the given event. Finally, these relations were used to evaluate the detectability and estimate the location error.

Signal amplitude is estimated with the attenuation model of the Moon, which refers to a seismic Q model. Geometric spreading was modeled with $1/R$ where R is the length of the ray path between the source and the station [6]. Though some models exist for seismic Q inside the Moon, there are still uncertainties especially for the deep regions. Thus to evaluate the results we got, we ran tests with various Q models. We referred to Nakamura et al [1] and Nakamura [3] for the location and the size-frequency distribution of the deep moonquakes.

In addition, we used additional seismic data from Apollo 17 Lunar Surface Gravimeter. Kawamura[5] discussed its application for seismic analyses and identified new deep moonquake nests. These new identified deep moonquake nests were also included in the discussion.

Result: Figure 2 is the example of detectability of the network for an event with average size deep moonquake. The detactability of the network can be evaluated by the ratio between area of the lunar surface and the area detectable with the network. This detectability can be used to correct the number of event detected with the network.

Discussion: One of the feature pointed out for the distribution of the deep moonquakes is its lack of nests at the lunar farside. We tested this by comparing the size frequency distribution of the deep moonquake events on the lunar nearside and the farside. Figure 3 shows the corrected size frequency distribution. To compare the size frequency distribution of the statistics, we fitted the data with simple power law and compared the result. The results shows that the lunar farside is as active as the lunar nearside. As it was pointed out before, there can be a large uncertainties for the seismic *Q* model, which can bias our results. We ran tests with high Q model (*Q* +50% and *Q* +100%) and low *Q* model (*Q* -50%). In all cases, the size frequency distribution at the lunar farside was comparable to that of the lunar nearside and we can conclude that the deep moonquake activity on the lunar farside can be as active as the lunar nearside.

Summary and Conclusions: We carried out a quantitative evaluation of the network observation bias of the Apollo seismic network. With the estimation the detectability of each station and the overall network, we were able to correct for the observation of the network. With the correction of the detectability, we compared the size frequency distribution of deep moonquakes on the lunar nearside and farside. Though the observable area of the lunar farside is limited compared with that of the nearside, we found that the deep moonquake activity on the lunar farside can be as active as the lunar near side.

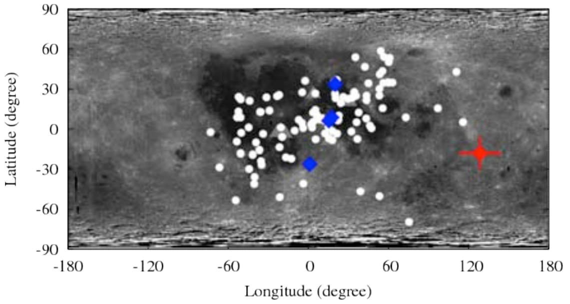

Figure 1 The spatial distribution of the known deep moonquake nests. The gray triangles show the locations of Apollo stations. The white circles show the known nests listed in Nakamura [3]. The blue and red boxes show the newly identified deep moonquake nests by Kawamura[5].

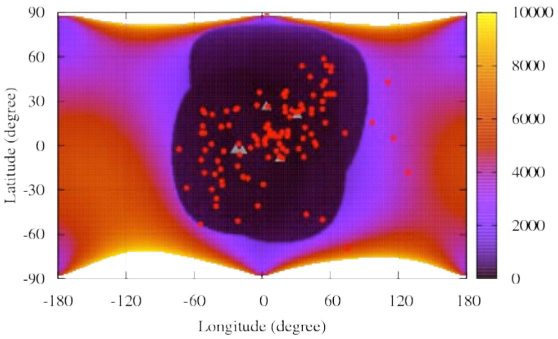

Figure 2 Detectability of the seismic network. The color contour shows the estimated location error. The blank region shows the area that signal from the seismic source in that region will be detected with 3 or less stations and unlocatable. We assumed the focal depth of 933 km and the representative amplitude of 3.9×10^{-6} m, which is a deep moonquake with an intermediate magnitude. The red dots show the location of the deep moonquake nest including the nests newly identified in this study.

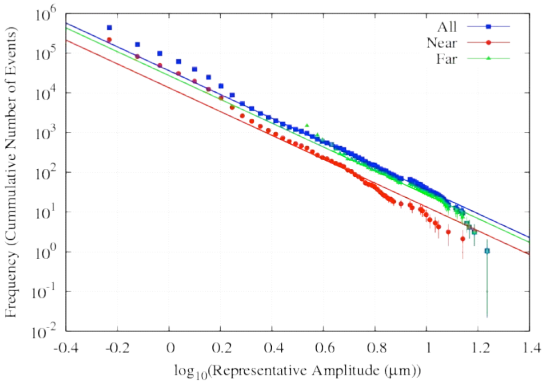

Figure 3 Corrected size frequency distribution of deep moonquakes on the lunar nearside, farside and whole lunar surface.

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