Classification of deep moonquakes using machine learning technique and application of it to lunar science and exploration

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A lot of lunar seismic events had been observed by 4 seismic stations deployed at Apollo 12, 14 15 and 16 sites through NASA Apollo mission from 1969 to 1977. Deep moonquake which occurs at depth of about 700-1200 km is most frequent lunar seismic event, and 106 sources have been located. The deep moonquake events occurred from the located source have been analyzed to investigate the lunar deep structure (e.g., Lognonn et al., 2003, Matsumoto et al., 2015). We know that the deep moonquakes occur repeatedly related with tidal force worked on the lunar interior and the waveforms of the events generated from the same source are similar (Nakamura et al., 1982). The sources of many deep moonquake events have been identified using the similarity of the waveforms (e.g., Nakamura, 2003). On the other hand, about 20% of the discovered lunar seismic events are still unclassified and about several hundreds of the deep events are unlocated. This fact indicates that the previous identification of the deep moonquake sources using the waveform similarity is not necessarily sufficient. In the previous studies, the waveforms of deep moonquake in time series are mainly analyzed to classify the sources using the similarity (e.g., Nakamura, 2003, Bulow et al., 2005), and they would not be enough to classify the sources. Therefore, we have investigated new parameters to classify the deep moonquake sources efficiently using the supervised machine learning technique.

In this study, we analyzed the deep moonquake events occurred from the known active sources observed at Apollo12 station. Firstly, we have investigated effectivity of power spectral density (PSD) in frequency domain to classify the deep sources using one of conventional machine learning technique; Support Vector Machine (SVM). This result has shown that the PSD using 15 minutes' data from arrival of P-wave are more effective to classify the sources compared with waveform in time series (Goto et al., 2013, Kato et al., 2016). Secondary, most effective machine learning technique for classification of the deep source has been studied, and we found that Neural Network has the best availability among five representative method. Then, it is often difficult to extract the effective parameters from the waveforms due to small amplitude and strong scattering of the waveforms. From the reason, we have investigated positional relation between the Moon and other planets at occurrence time of each deep moonquake as the parameters for the classification without using the waveforms, because it is known that deep events occur related with relative position (that is tidal force) among the Moon, the Earth and the Sun (e.g., Lammleign, 1977). This investigation has shown that relative position and velocity between the Moon and the Earth were important to identify some deep moonquake sources (Kato et al., 2017).

We found that these new parameters and method for classification of the deep sources are available to identify the source of the unlocated deep events (Kikuchi et al., 2017). Most deep moonquake source have been located in lunar near-side and there are only small number of sources in lunar far-side. However, Nakamura (2005) describes that some deep moonquake events which may occur from undiscovered far-side sources are detected at only one or two Apollo stations. Though this number is insufficient to locate the source from travel-time analysis, if we can identify that the unclassified events generate from the same far-side source and increase the observation points using our new method, we may be able to locate that and discover new far-side sources. This discovery will give new knowledge about activity of far-side deep events, internal structure in lunar far-side and the lunar dichotomy. Then, it can be expected that we can discover a lot of new deep moonquakes in sequential seismic data observed during about 7 years using the new parameters such as PSD. In future lunar seismic experiments such as SELENE-2 (Tanaka et al., 2008) and Approach (Yamada et al., 2016), we can deploy only one or two seismic stations, and the number is insufficient to locate the deep moonquakes. In this case, if we can identify the source of detected deep events using the positional relation between the Moon and other planets, we will be able to obtain new travel time data of deep moonquakes on the future missions in spite of a few seismic stations.

Keywords: Deep moonquake, Machine learning technique, Analysis of moonquake waveform, Lunar interior structure, Lunar exploration