INVESTIGATING DEEP MOONQUAKE CLUSTERING USING THE SCATTERING TRANSFORM.

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Introduction: The Apollo Lunar Surface Experiment Package (ALSEP) is comprised of four seismic stations which were placed on the near side of the moon between 1969 and 1972, and they recorded lunar seismic activity until instrument shut-off in 1977 [1]. The network detected approximately 12000 seismic events, the most numerous of which are deep moonquakes (DMQs), which manifest as repeating tidally-linked signals located in regions called clusters, or nests. Here we explore the ability of a machine learning technique, the wavelet scattering transform, to detect patterns within a single DMQ cluster and analyze those patterns' relationships to lunar ephemeris.

Background: Deep moonquakes (DMQs) are repeated lunar seismic events occurring at focal depths between 800 km and 1200 km [2]. These events originate from 319 source regions, or clusters, and are observed to have 13.6-day, 27-day, and 206-day periodicities, indicating that the tidal stresses caused by the interaction between the Earth, Moon, and Sun play a role in the DMQ source mechanisms [3]. DMQ events have been valuable for determining lunar interior structure, as their arrival times can be used to derive mantle P- and S-wave velocities [4] and other body waves, such as core reflections [5].

The identification and classification of events in the ALSEP data was initially conducted using visual inspection of day-long seismograms [1]. Computational advancements have enabled the application of new techniques that identified more DMQs: a combination of waveform cross-correlation and cluster analysis identified 5905 new moonquakes and 88 new DMQ nests [6], and a cross-correlation algorithm combined with an algorithm to de-glitch Apollo data resulted in 123 new events for the A1 DMQ cluster alone [7]. The Apollo seismic data is difficult to analyze because of low signal to noise ratio and instrument glitches that create spikes and/or gaps in the data time series.

Current Work: Previously, we used a convolutional neural net (CNN) to identify and classify events from the two largest DMQ nests, the A1 and the A8 clusters, identified in the most recently updated lunar seismic event catalog [7, 9] and recorded on the Apollo 12 long period (LP) three-component seismometers. Spectrograms were made from these events and used to train several image classification CNNs to identify the difference between an A1 and an A8 DMQ.

Several different CNNs were trained and tested on the spectrograms; despite various modifications to the CNN architecture the validation accuracies did not improve beyond 70.1%, indicating that the algorithms did not learn effectively. These results imply that CNNs are inefficient with the number of events in the 2 nests (even with an incorporation of synthesized events to augment the final datasets).

Instead of CNNs, an alternative method called wavelet scattering transforms will be used to analyze the DMQ events. Scattering transforms are an adaptation of traditional CNNs and are designed to analyze and classify high-dimensional data [10]. In a scattering transform, an input signal is convolved with a family of complex wavelets that span all of frequency space. Scattering transforms behave similarly to CNNs; however they do not learn the same way, so they do not require large datasets. An additional advantage is that scattering coefficients generated by the convolution of the wavelets with the data are statistically interpretable in a way that the hyperparameters of a CNN are not. Scattering transforms, done iteratively to the second or third order, yield a compact set of coefficients that contain statistical information from the original data, as shown in Figure 1. These coefficients are then sequenced by similarity to reveal overarching patterns in the dataset.

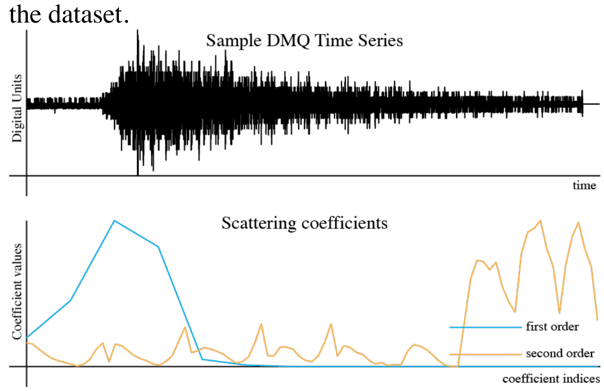

Fig. 1. A sample deep moonquake event time series with their representative first- and second-order scattering coefficients.

Preliminary Findings: Scattering transforms were performed on a subset of A1 DMQ events with high signal to noise ratios to demonstrate proof of concept. The first order scattering coefficients when sequenced correlates with a pattern in power spectra from high power to low power at low frequencies. This trend also correlates to a trend of Earth-Moon separation from large values to small values, as shown by Figure 2.

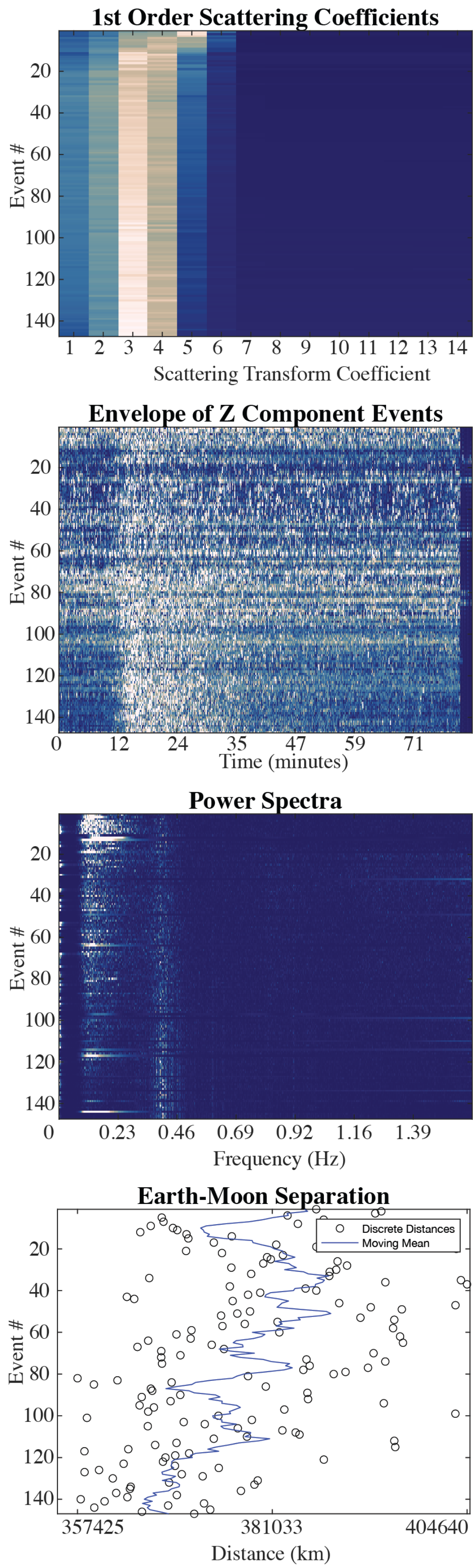

Fig. 2. Sequenced first order scattering coefficients; the same sequencing is executed on the corresponding envelope of vertical-component events, power spectra, and Earth-Moon separation.

Future Work: The pilot study demonstrates that scattering transforms can highlight patterns within a single DMQ nest, and that these patterns correlate with physical parameters that may drive the focal mechanisms behind the events. Further analysis will be done on the rest of the A1 DMQ nest after an appropriate instrument response removal and glitch removal scheme can be used to include the previously-excluded events. The analysis will then be expanded to the other DMQ nests and other Apollo seismic instruments.

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