Simulations of Lunar Seismic Wave Propagation: Evaluation of Scattering Effects by Heterogeneous Media and Surface and Moho Topography

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1. Background

Originating from the installation of seismometers on the lunar surface in the Apollo missions (11, 12, 14, 15, 16, 17) (e.g., [1]), seismology outside our planet began and has contributed to improving our knowledge about seismicity and the internal structure of the Moon. At the same time, the observed seismic signals puzzled us for their extremely long-lasting coda and spindle shape, unlike typical earthquake signals (e.g., [2]).

Through data analysis, laboratory experiments, and numerical simulations (e.g., [3-6]), it turned out that the intense scattering due to a mechanically fractured medium, called megaregolith, strongly affected the wave propagation.

2. Main scope

While previous studies on lunar scattering mainly focused on megaregolith, it is known that scattering can be caused by topographic features, such as mountains and variations at the Moho boundary (e.g., [7]).

Unlike the Apollo landing sites, future lunar missions carrying seismometer packages plan to go to polar regions / the far side of the Moon, where various topographic features have been reported (e.g., craters, mantle plugs).

In order to better understand the scattering mechanism on the Moon and to help future seismic data interpretation, this study is trying to evaluate the seismic scattering caused by topographic features and megaregolith through numerical simulations.

3. Test field

As a test area, I selected Szilard crater (34 °N, 106 °E) for hosting several large craters and a distinct mantle plug (Fig 1). Currently, I consider the wave propagation of an isotropic radiation (i.e., meteorite impact analog) at the south margin of Szilard crater (32 °N, 106 °E).

4. Wave propagation simulation

The OpenSWPC [10] was used to compute the lunar seismic wave propagation because it allows us to compute high-frequency signals (~ 2 Hz) stably and to include both topography and random media in the simulation.

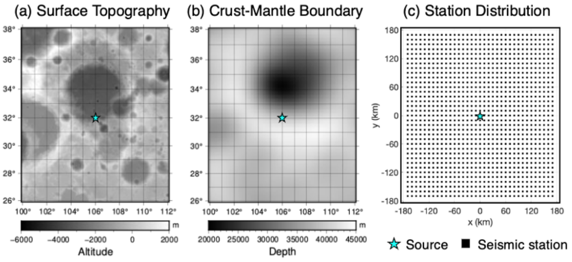

Fig 1. (a) Surface topography map [8], (b) Crust-mantle boundary map [9], (c) Location of virtual stations.

Following Onodera et al. [5], I constructed the internal structure model using porosity and empirical V_p and V_s models derived in the previous studies (e.g., [11-12]) (Fig 2). As for random media, the autocorrelation function with exponential form (e.g., [13]) was employed, where characteristic scale of 0.65 km with 10 % (1σ) velocity perturbation was assumed after [5].

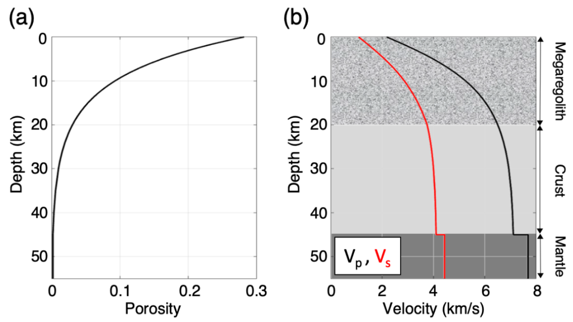

Fig 2. (a) Porosity and (b) velocity models.

5. Results

Fig 3 compares snapshots of two simulation cases: (a) 3D: surface & Moho topography, (b) 3D-r: topography + random media. Interestingly, most seismic energy is trapped in the low-velocity layer near the surface in both cases (3D & 3D-r), meaning the wave propagation seems mainly characterized by the near-surface structure for an impact-induced seismic event (e.g., see cross-section image in Fig 3a-3b).

To observe the difference in wave propagation, I retrieved time series data along the north and south paths from the source. Fig 4 compares the waveform and envelopes at the Apollo long-period (LP) frequency range (0.3 – 1.5 Hz). Even though there is a large topographic variation at surface/Moho from the south to north path passing over the seismic source, little difference is observed between the waveforms/envelopes along south and north paths (blue and red signals in Fig 4). These results indicate that, in the Apollo LP frequency, near-surface heterogeneous structure (megaregolith) plays a dominant rule in characterizing lunar seismic signals, which verifies the previous interpretations (e.g., [2][5]).

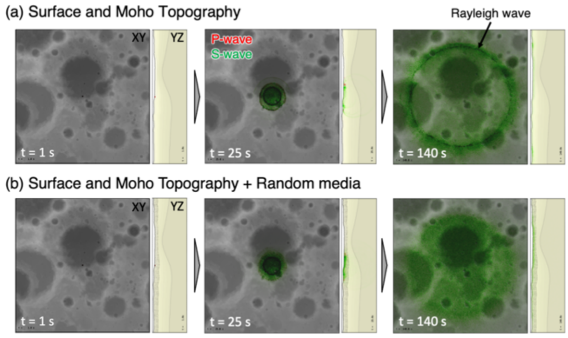

Fig 3. Snapshots of simulated seismic wave on bird-view & N-S cross-section along 106°E for two simulation cases including (a) surface & Moho topography and (b) topography and random media, respectively.

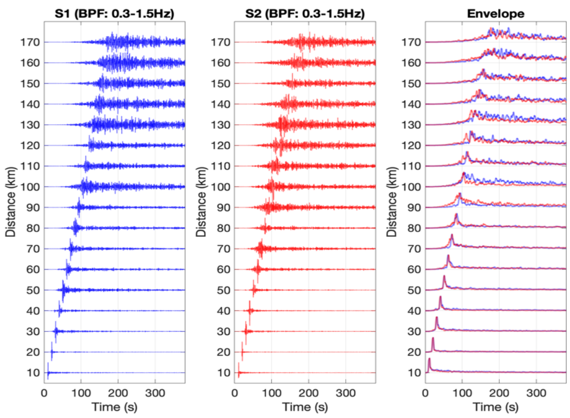

Fig 4. Waveforms and envelopes along the north path (S1) & south path (S2) (0.3 – 1.5 Hz).

On the other hand, moving to the lower frequency (0.05 – 0.3 Hz), a clear difference shows up (Fig 5) depending on the paths. This is interpreted as the dominant scattering effect varies with frequency. In the Apollo's frequency band, the scattering by the megaregolith was dominantly observed. Yet, at lower frequencies (~ 0.1 Hz), topographic scattering gets more dominant. Actually, the latter is more useful to determine the crustal thickness which still carries uncertainty to this day. Based on these results, I will propose a required specification for future lunar seismic observations with broad-band seismometer to better constrain the crustal structure of the Moon.

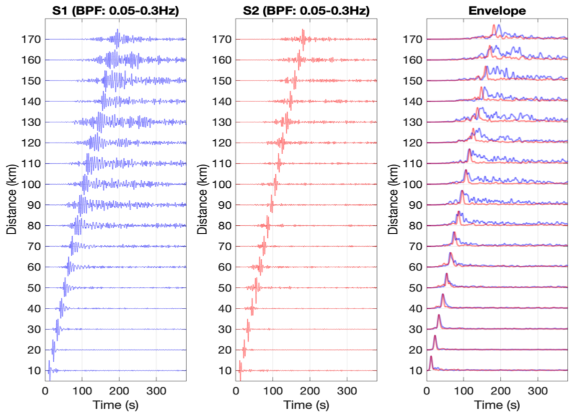

Fig 5. Waveforms and envelopes along the north path and south path (0.05 – 0.3 Hz).

Ongoing analysis

To perform more in-depth evaluation of different scattering effects (e.g., topography, random media), I am checking how much the coherent wave patterns are preserved from the source. Fig 6 displays preliminary results, where 2D correlation map was produced by computing cross-correlation between a reference station and other stations distributed over the workspace shown in Fig 1c.

As in Fig 6a, even with random media (megaregolith), the wave correlation is relatively preserved (CC > 0.5) over long distances. On the contrary, introducing topography leads to the decrease in average correlation and produces an asymmetric pattern (Fig 6b). This kind of numerical experiment will help us interpret the obtained seismic data in future, especially with regional network observations. Further quantitative evaluation will be continued and the results will be submitted to a peer-reviewed article in FY2026.

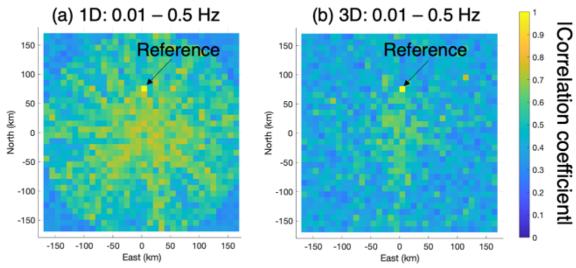

Fig 6. Correlation map for (a) 1D and (b) 3D simulation cases. Each simulation includes random media in the upper crust. The color indicates the absolute value of the cross-correlation coefficient between a reference station and other stations shown in Fig 1c.

Acknowledgement

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