# Investigation of Lunar Crustal Structure in Local to Regional Scale via Seismic Wave Propagation Simulation

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## 1. Introduction

The subsurface and crustal structure of a planet is a fundamental piece of information to understand past geological evolution, such as volcanism and tectonics. On the Moon, seismic data obtained during the Apollo missions, where both active and passive observations were carried out (e.g., [1][2]).

Even though many studies analyzed the Apollo seismic data, the obtained internal structure carries large uncertainties due to the sparse network, narrow-band observation, and influence of intense scattering. In this study, instead of solving an inverse problem using the Apollo data, I try to give new insights into the lunar interior in a forward way, which was barely applied in planetary seismology before.

## 2. Investigation of Near-Surface Structure

### 2.1. Background

The local scale structure (10 – 100 m) was investigated by both active and passive seismic data (e.g., [2][3]). Cooper et al. (1974) [2] analyzed the Active Seismic Experiment (ASE) data, where an astronaut generated ground shaking using a thumper rod and seismic signals were recorded by three geophones (Figures 1a-c), and gave the first estimation of 1-D velocity structure at the Apollo 14 landing site. Later, Tanimoto et al. (2008) [3] estimated 1-D velocity structure by applying the noise cross-correlation approach to the Apollo 17 Lunar Seismic Profiling Experiment (LSPE) data. In this study, building on the previously proposed models, I will (i) check whether the existing structure model can reproduce the observations via wave propagation simulation using OpenSWPC [4] and (ii) apply the obtained knowledge to designing an active seismic exploration in future lunar exploration.

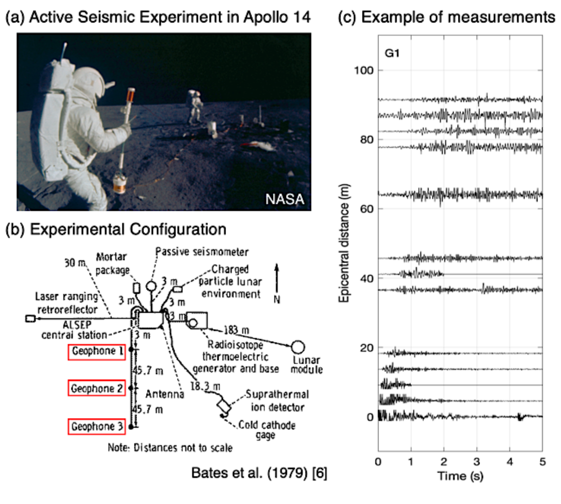


**Figure 1.** (a) Image of the ASE performed in the Apollo 14 mission. (b) Location of geophones used in the experiment. The thumper was hit on various sites along the line where geophones were aligned. (c) Examples of seismic data during the ASE.

### 2.2. Forward modeling

Forward modeling was performed under a 400 m × 400 m × 200 m box with a scattering layer inserted in the first 15 m, where a vertical single force was assumed as an input source. Here, I show the results of Apollo 14 ASE data recorded at 46 m away from the source.

### 2.3. Key results

First, assuming Case 1 model, which was constructed based on the results by Tanimoto et al. (2008) [3], I computed the vertical ground velocity and compared it with the Apollo observation (Figures 2a-b). I found that the simulated waveform showed a strong peak of Rayleigh wave, which cannot be confirmed in the Apollo seismic recording. Although several attempts were made by changing scattering properties, the results were not improved significantly. This means that, in this spatial scale, the velocity structure characterizes the waveform more dominantly than the scattering media. Eventually, inserting a very low velocity layer (Case 2 in Figure 2a) made a significant improvement of the synthetic waveform (Figure 2b).

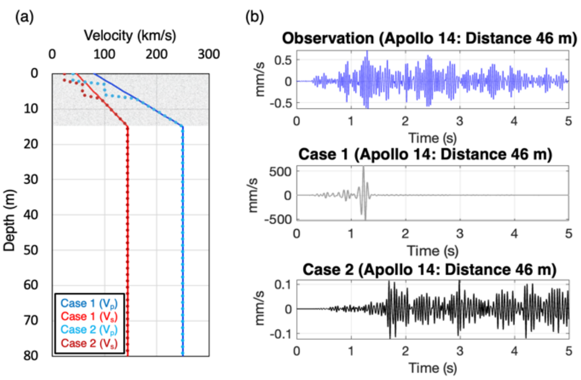


**Figure 2.** (a) Input velocity structure models. The gray filled area marks the scattering layer. (b) Waveforms of the Apollo observation and simulation outputs for Case 1 and Case 2.

In future computations, I will simulate other Apollo ASEs and also consider how to optimize future lunar seismic experiments.

## 3. Assessment of Regional Scale Topography Effects on Seismic Wave Propagation

### 3.1. Background

Large topographic variations are one of the dominant influencers on lunar seismic wave propagation, besides the intense scattering and extremely dry environment. So far, Onodera et al. (2022) [5] conducted wave propagation simulation at the Apollo 12 and 14 landing sites and succeeded in reproducing the Apollo seismic data, leading to constraining the scattering parameters in a forward way. Yet, as the Apollo 12 and 14 sites are relatively flat, it remains uncertain how much large topography and/or mantle plug affects the lunar seismic wave propagation. Some of the planned lunar seismic explorations consider the farside of the Moon as landing sites, where larger topographic variations are expected than the nearside. Therefore, evaluating the expected influence of topography variations would be helpful for designing seismometers and interpreting the observed signals. In this study, focusing on one of the craters situated in the farside of the Moon (Szilard crater), I try to clarify its contribution to seismic wave propagation.

### 3.2. Workspace and Setups

As shown in Figure 3a, I prepared a workspace around Szilard crater (N/S/W/E=38°N/25°N/98°E/112°E), where lots of several km-size craters coexist. Also, a large mantle plug is confirmed below the Szilard crater (Figure 3b). Thereby, comparing various patterns, such as (i) 1-D layered structure, (ii) surface and Moho topography + layered structure, (iii) surface and Moho topography + layered structure + random media, would give me an initial speculation about the contribution of each factor.

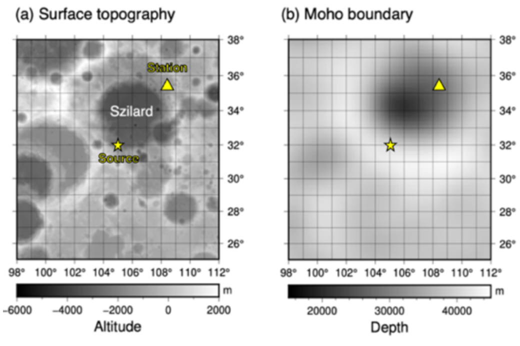


**Figure 3**. (a) Digital elevation model around the Szilard crater. The gray scale indicates the altitude measured from the mean radius of the Moon (1737.4 km). Note that 1° is equal to 30.3 km. The original data were provided by Barker et al. (2016) [7]. (b) Topography of the crust-mantle boundary (Moho) estimated by Wieczorek et al. (2013) [8].

### 3.3. Initial results

Figure 4 displays the waveforms observed at the Station in Figure 3 under the conditions (i) – (iii) explained in Section 3.2. In the simulation, a surface impact was assumed as a source. Case (i) shows a sharp peak of the Rayleigh wave (~160s). Including topography significantly scatters the Rayleigh wave and makes the waveform more emergent, although the S-wave arrival is still detectable at around 90 s (Figure 4 (ii)). Furthermore, adding random media diffuses not only the Rayleigh wave but also body waves, and eventually the waveform gets spindle-shaped as seen in moonquakes recorded in the Apollo lunar seismic data.

A more quantitative discussion will be brought by future analyses. Yet, a key finding here is that a large topography, in addition to random media, can significantly affect the characterization of the lunar seismic signals, which could not be assessed at the Apollo 12 and 14 sites where a relatively flat topography exists [5]. Future simulations and analyses will focus on a quantitative comparison between stations located at different sites, which will be useful to design future lunar seismic explorations better.

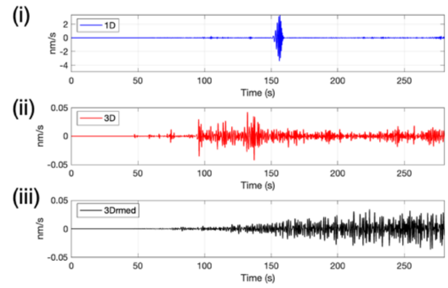


**Figure 4**. Output waveforms for Cases (i) – (iii) in Section 3.2.

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