THE EFFECT OF FREE-SURFACE TOPOGRAPHY ON SEISMIC WAVES IN THE MOON. N. C. Schmerr[1], and E. Matzel[2], and S. R. Ford[2]. [1]Planetary Geodynamics Laboratory, Goddard Space Flight Center, Code 698, Greenbelt, MD 20771, nicholas.c.schmerr@nasa.gov, [2]Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, CA 94550, matzel1@llnl.gov, ford17@llnl.gov.

Introduction: During the Apollo era, a four station seismic network was deployed upon the nearside of the Moon, and returned the first-ever seismic dataset for another body in the Solar System (Fig. 1). The Apollo passive seismic network consisted of four separate stations, deployed on the Moon by the Apollo 12, 14, 15, and 16 astronauts from 1969 to 1972, and remained in continuous operation until 1977. Each seismic package consisted of a three-axis long period (LP) and a short period (SP) vertical axis seismometer, with peak sensitivities in 0.45 Hz range (LP) and 8 Hz range (SP), and sample rates of ~0.15 s (LP) and ~0.02 s (SP) [1]. The seismic array was arranged on the nearside of the Moon in the form of an equilateral triangle, with each station approximately 1200 km apart, and the Apollo 12 and 14 sites located at one vertex of the triangular array (Fig. 1).

The seismometers recorded ~13,000 seismic events on and within the Moon [2, 3]. These are categorized into several type of moonquakes, the most numerous being deep quake "swarms" of multiple closely located events at 700-1000 km depth [4]. Also detected were 8 artificial impacts, 32 shallower quakes, and 26 meteoroid impacts [5]. Thus, the Moon is a seismically active body, with seismic events up to a moment magnitudes of near 5.0 [6], allowing the application of terrestrial seismic techniques to study the dataset. The entire lunar dataset is freely available for download on the Incorporated Research Institutions for Seismology Data Management Center (IRIS-DMC) website.

This dataset has been incredibly fruitful in constraining a number of important parameters relevant to the thermal and compositional evolution of the Moon, as it provided estimates for lunar crustal thickness and structure [7], seismic wave velocity and the bulk structure of the lunar mantle [8], and provided constraints on the attenuation and scattering structure of the lunar interior [9, 10]. However, many primary questions remain about the Moon's internal structure, including the size, composition, and state of the core, the detailed vertical structure of the lunar mantle, the global thickness of the crust, the nature of seismic scattering in the crust and mantle, and the extent of lateral heterogeneity in all these regions. Constraining these properties has important implications for the formation and dynamical evolution of the Moon.

Here we investigate the effects of the lunar surface topography on the propagation of seismic waves to improve estimates of lunar crustal structure and scattering properties. Topographic roughness can strongly amplify seismic waves traveling along the surface near the source and produce scattering of the seismic wavefield [11]. There are numerous approaches to modeling the effect of free surface topography on seismic waves in elastic bodies; a primary conclusion is that topographic effects are most pronounced in regions possessing steep slopes and where topography is on the order of the wavelength of the seismic waves [12]. These models suggest that topography on the Moon strongly affects the character of the lunar seismic wavefield. Quantifying the contribution of topography will greatly improve inversions and forward models attempting to determine lunar crustal and mantle structure from the Apollo and future seismic datasets.

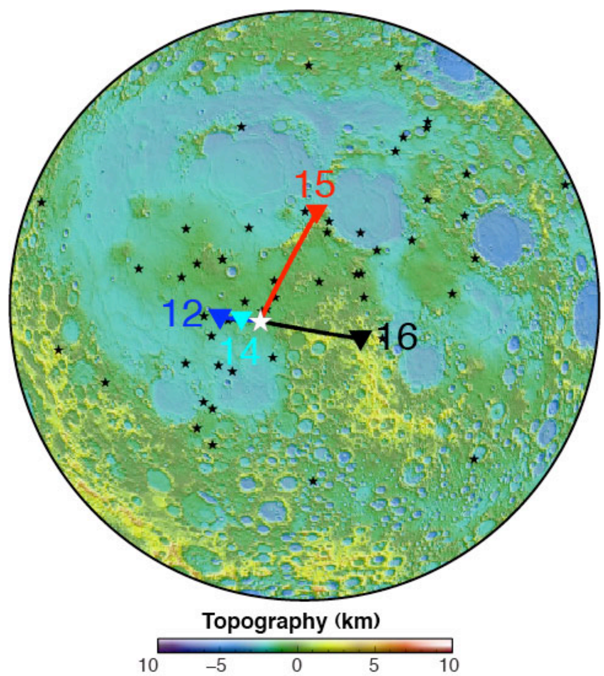

Figure 1. Topography of the Moon from Lunar Orbiter Laser Altimeter and the locations of the Apollo seismic stations (triangles). Moonquakes are shown as stars. The location of the impact of the Apollo 17 S-IVB is shown as a large white star.

High-resolution topography of the lunar surface has recently been obtained by the Lunar Orbiter Laser Altimeter (LOLA), an instrument on the Lunar Reconnaissance Orbiter mission [13]. The LOLA dataset has a lateral resolution of approximately 60 m, and is one of the most detailed surface topography measurements in the Solar System. Lunar topography spans elevations ranging from -9117 m to 10,783 m, and is highly variable owing to the diversity of geologic terranes, ranging from the heavily-cratered anorthositic highlands to the large basins of basaltic maria [13]. Slopes on the Moon range from 15-25º or greater near crater rims, to < 5º in the mare basins [13]. Local relief can be extreme, especially in the vicinity of crater rims (Fig. 2). The LOLA results indicate topography will strongly affect the lunar seismic wavefield.

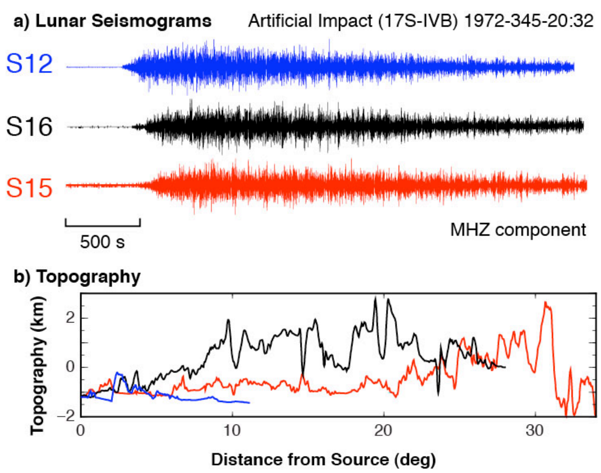

Figure 2. Apollo seismograms and topographic profiles source and stations shown in Fig. 1. a) Vertical component seismograms showing the character of the lunar seismic wavefield. Instrumental noise at S14 made the data from that site unuseable. b) Topographic profiles along the surface paths for each event-station path, the color of each path corresponds to its respective seismic station.

Approach: Forward modeling of topographic effects requires the consideration of 3-D wave propagation, an approach that has become routinely accessible with large-scale parallel processing and faster processors. To model the effects of free surface topography on wave propagation in the moon, we have adapted the 3-D spectral element method code SPECFEM [14] for lunar elastic parameters and radius. SPECFEM allows us to investigate the effects of topography down to 1 minute resolution in a global elevation model, as well as the study the contribution of 3-D lateral and vertical heterogeneities to seismic amplitudes and travel times. We run the SPECFEM code to obtain lunar seismograms. To investigate the effects of small-scale topography at higher seismic frequencies, we also adapt the Wave Propagation Program (WPP) seismic code [15] to lunar parameters and radius. Both approaches are benchmarked against synthetic seismograms from a lunar adapted 1-D reflectivity code [16].

Comparison to Data: We compare the results of the forward modeled seismograms from SPECFEM and WPP methods to the data from the Apollo stations. Topographic effects are more pronounced for impacts and shallow moonquakes, owing to their greater paths through the lunar crust (Fig. 2). Seismic velocities in the uppermost kilometer of the lunar crust are quite low (≤ 0.7 km/s for *P* and ≤ 0.3 km/s for *S*) and have little intrinsic attenuation, generating significant scattering in the lunar crust [7]. These effects create lunar seismograms that are very different from their terrestrial counterparts, with only weakly emergent *P* and *S* waves followed by a long ringing coda [17]. We produce synthetics for topography sampled at several different wavelengths and dominant frequencies of the seismic waves to quantify the effect of these parameters on the retrieved seismic wavefield. We have adapted a median weighted despiking algorithm to remove instrumental noise from the Apollo seismic dataset. Initial results indicate that the moonquakes centered in the cratered highlands experience the strongest effects from topography.

Expected Results: Our modeling study will allow us to investigate the nature of seismic scattering in the lunar interior, by providing an estimate for the contribution of surface topography to this result. Additionally, this method will provide an estimation of where topographic effects are potentially the strongest on the lunar surface and guide future deployments of seismic instrumentation on the Moon [18]. In addition, the SPECFEM and WPP techniques are highly adaptable for other planetary bodies in the Solar System. Surface topographic effect will be highly pronounced in irregular bodies such as asteroids and comets, and our approach is valid for investigating the effect of topography on seismic wave propagation in these bodies as well. Our research will also provide information about the character of the seismic wavefield at the location of potential landing sites for future seismometer deployments.

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