

SEISMIC INTERFEROMETRY ON THE MOON FOR NEAR-SURFACE EXPLORATION.

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Brief Presenter Biography: Ban-Sok Shin received his Doctoral degree in Electrical Engineering (with distinction) from the University of Bremen, Germany, in 2020. Since 2019 he has been a postdoctoral researcher in the Swarm Exploration Group at the German Aerospace Center, working on seismic exploration using multi-agent networks.

Introduction: Upcoming missions under the Artemis program and concepts such as Cooperative Autonomous Distributed Exploration Rovers (CADRE) and ETH's LunarLeaper seek to identify critical resources like near-surface ice and safe subterranean cavities (e.g., lava tubes)[1][2][3][4]. Seismology has long underpinned our understanding of planetary bodies' interiors. For example, the Apollo network on the Moon revealed deep moonquakes and near-surface structures and In-Sight's single-station observations led to new discoveries on Mars [5][6]. Additionally, seismic exploration is a common method to gather information on more near-subsurface structures. Although static seismic arrays (e.g., Lunar Environment Monitoring Stations) are planned as part of Artemis III, mobile multi-agent networks offer broader spatial coverage by repositioning seismometers as needed and to improve confidence in results from collected seismic data [7].

The NEPOS (Near-Surface Seismic Exploration of Planetary Bodies with Adaptive Networks) project pursues the development of autonomous rover arrays for seismic exploration in strongly scattering environments present on the Moon. Key objectives include:

1. Designing methods for active and passive planetary seismic surveys,
2. Implementing mobile near-surface imaging strategies, and
3. Prototyping an adaptive sensor network for analog field tests on Earth.

Ambient Noise Interferometry in Scattering Media: Ambient noise interferometry correlates naturally occurring passive signals (e.g., thermal moonquakes) to recover the empirical Green's function between sensors [8]. Such methods circumvent the need for active sources and have already shown promising results for lunar data from the Apollo 17 Lunar Seismic Profiling Experiment (LPSE) [9][10][11]. Ambient noise interferometry leverages the dispersive behavior of Rayleigh waves. In practice, the group velocity is determined by dividing the travel distance by the travel time, while the

continuous wavelet transform (CWT) is employed to produce a scalogram that captures the energy distribution across time and frequency. This scalogram facilitates travel time picking by identifying the frequency-dependent arrival times of seismic energy [8]. Preliminary findings using forward modeling in a frequency range 3-8 Hz indicate that passive methods allow mapping of ice-bearing rock, whereas deeper structures (e.g., lava tubes) require lower-frequency energy.

Position and Time Uncertainty in Multi-Agent Systems: Multi-agent systems face specific uncertainties in localization and timing due to the absence of GPS or similar positioning aids, e.g. on the Moon. Agents estimate positions via inter-rover radio-frequency ranging, inertial navigation, or local references [12]. Our analysis indicates that realistic ~ 1 m [13] localization errors over ~ 60 m distance introduce small velocity shifts, which remain acceptable for near-surface imaging (see Figure 1).

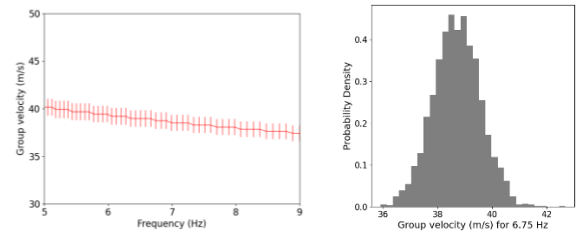


Figure 1. Rayleigh wave velocity estimates with standard deviation (left) in presence of positional uncertainty. Exemplary histogram for 6.75 Hz (right).

In addition, instability of receiver-local clocks distort the correlation of seismic measurements. However, periodic synchronization (e.g., every 50 s) can mitigate these effects, ensuring that even comparatively unstable, low-cost ultra-wideband (UWB) clocks yield sufficiently accurate recovery of the empirical Green's function [14][15] (see Figure 2).

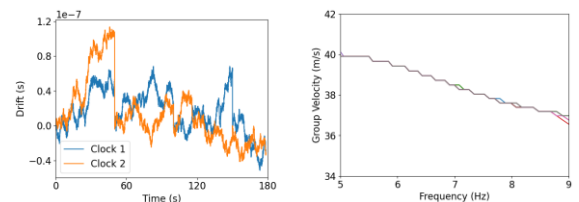


Figure 2. Exemplary clock drifts with 50 s synchronization interval (left) and 1000 resulting Rayleigh wave dispersion curves (right).

A further source of time uncertainty arises from the time-frequency resolution of the CWT. The trade-off is dictated by the Heisenberg uncertainty principle. As a consequence, when picking the arrival time from the scalogram, the finite energy spread around that time-frequency “location” contributes to the uncertainty in the velocity estimates [16]. The cumulative impact of positional errors and CWT-processing uncertainties on the velocity estimate is shown in Figure 3.

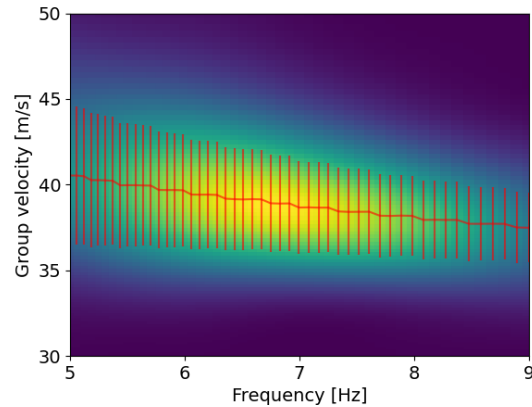


Figure 3. Rayleigh wave dispersion curve with standard deviation due to position and CWT-processing errors. The background displays the scalogram.

Toward Optimal Experimental Design: Bayesian experimental design offers a way to maximize the expected information gained by optimizing sensor layouts to reduce posterior uncertainties in subsurface velocity estimates. Recent variational methods [3] and near-real-time design strategies [17] could be extended to manage the described uncertainties by making them part of the likelihood function. Applying such frameworks to multi-agent networks would enable the selection of seismic station locations that gather the most informative data for imaging ice-rich layers, lava tubes, or other high-priority subsurface targets.

Conclusion: Flexible mobile seismic networks represent a promising avenue for lunar near-surface exploration. The NEPOS project brings together multi-agent navigation, ambient noise interferometry, and advanced design strategies while addressing limitations in positioning, timing, and wavelet-based time-frequency uncertainty. Planned analog tests on Earth (e.g., seismic measurement campaign to detect lava tubes and over realistic lunar regolith in the ESA/DLR LUNA analog facility) will further refine these methods.

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