LUNAR SUBSURFACE EXPLORATION BY MULTI-AGENT SYSTEMS USING SEISMIC AMBIENT NOISE INTERFEROMETRY.

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Introduction: With NASA's Artemis campaign, the Moon has reemerged as a prime target for scientific exploration, technology advancement, and as a stepping stone to Mars. Central to these efforts is the search for safe habitation sites and local resources. In particular, near-surface deposits of water ice could be harvested to support life support systems and provide fuel components, while large underground cavities - potentially lava tubes - offer natural protection from cosmic radiation, micrometeorite impacts, and extreme temperature fluctuations [1], [2].

Seismic exploration is a common method to gather information on the subsurface of planetary bodies. As part of Artemis III, Lunar Environment Monitoring Stations (LEMSs) equipped with seismometers will be placed in the Lunar south polar region to create a static network for long-term monitoring. However, mobile multi-agent systems equipped with seismic sensors would allow for adaptable sensor networks to cover larger exploration areas and to improve confidence in results from collected seismic data [3]. In this vein, NASA's Cooperative Autonomous Distributed Exploration Rovers (CADRE) mission scheduled for 2025 will demonstrate how collaborative planning and data gathering enables autonomous multi-agent exploration of the Lunar surface [4].

Similarly, within the NEPOS (Near-Surface Seismic Exploration of Planetary Bodies with Adaptive Networks) project concepts for mobile seismic arrays are developed that can operate autonomously to detect specific subsurface features while adhering to the navigation and communication constraints of multi-agent systems. A key goal of NEPOS is to optimize survey design and processing workflows for strongly scattering environments where uncertainties arising from multi-agent cooperation could degrade seismic results [5]. As part of this effort, this abstract explores how multi-agent positioning uncertainties impact seismic results, in particular focusing on ambient noise interferometry. Ambient noise interferometry uses naturally occurring passive signals to extract the empirical Green's function between receivers by cross-correlating their recordings [6], therefore alleviating the challenge of implementing an active source mechanism. It has been shown to provide sufficient data after only a few hours of recording under certain Lunar conditions [7].

Methodology: Similar to, e.g., [8], [9], our analysis focuses on Rayleigh wave group velocity for frequencies of 5-9 Hz. As Rayleigh waves are dispersive, they have a frequency-dependent velocity v_f. This is reflected in varying time lag t_f's picked from the maximum of the frequency-filtered Green's function, while the distance d between seismic receivers stays constant:

$$v_f = \frac{d}{t_f} \tag{1}$$

In a multi-agent system, receivers correspond to agents and the distance d is calculated using the agents' coordinates. Coordinates are determined by combining all radio-frequency distance measurements between all agents in reach. Due to measurement uncertainty, coordinate system choice, agent layout, and other factors, these coordinates exhibit uncertainty [10]. [11] have shown that in different real-world scenarios a root-mean square error (RMSE) of 0.9 m from true position is achievable. Additionally, each agent's clock drifts over time, leading to agent-specific t_f's. Therefore, synchronizing clocks among agents is necessary to mitigate this effect.

Here, we assess how positional and clock uncertainties affect seismic results. First, we sample receiver positions from independent, circular-symmetric bivariate normal distribution centered on their observed positions. Each variance is set to the RMSE of 0.9 m reported in [11]. Inter-receiver distances and resulting v_f's are calculated for 2500 draws. Second, we consider clock drift by shifting time stamps of recorded seismic data. We simulate 10 realizations of comparatively unstable, but low-cost Ultra-Wide Band (UWB) clocks by using the two-state clock model from [12] and UWB clock data from [13] with a 30 s synchronization interval (Figure 1).

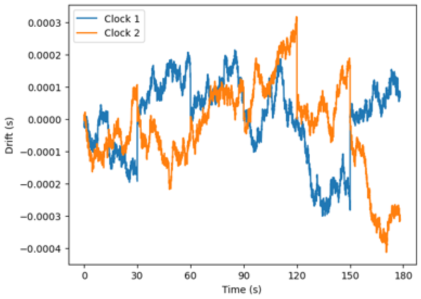

Figure 1. Two UWB clocks with 30 s synchronization intervals

Data and Processing: We apply our approach to data from the Apollo 17 Lunar Seismic Profiling Experiment (LSPE) [14]. Corrected inter-station distances are taken from [15] (Figure 2).

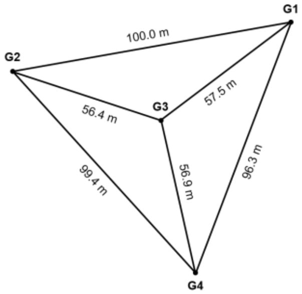

Figure 2. Geophone layout of the Apollo 17 Lunar Seismic Profiling Experiment (LSPE) with inter-station distances from [15].

The Apollo 17 LSPE primarily used active sources, but also collected passive data continuously between 15 August 1976 and 24 April 1977. We only use a single month, as its results are nearly identical to using the full time period [7]. After filtering the data to 5–9 Hz and applying spectral whitening, we cross-correlate 30-minute windows of measurements of all six station-pairs using MSNoise [16]. The resulting correlograms are then stacked together. We focus on receiver pair G3-G4, as its empirical Green's function has the highest signal-to-noise ratio after stacking [9].

Results: With only positional uncertainties, the resulting velocity estimates' mean match the v_f's calculated using the original 56.9 m distance between G3-G4, while standard deviations range from 0.90 to 0.83 m/s (decreasing at higher frequencies). The velocity estimates appear to follow a normal distribution (Figure 3).

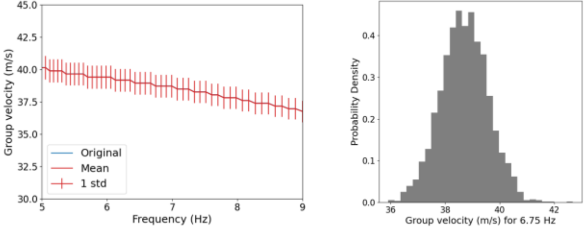

Figure 3. Rayleigh wave velocity estimates (left) in presence of positional uncertainty. Exemplary histogram (right) for 6.75 Hz.

Drifting UWB clocks with a synchronization interval of 30 s on G3 and G4 do not alter the resulting v_f's (Figure 4). Therefore, we do not combine positional uncertainty and clock drift in a unified simulation, as the result would match that of the positional uncertainty simulation.

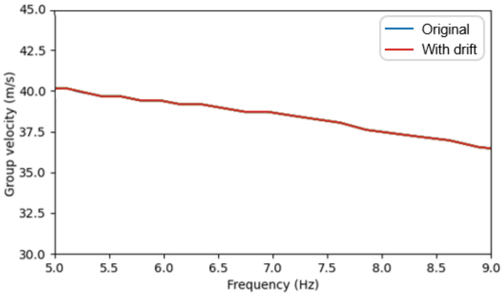

Figure 4. All 10 results from drifting clocks overlap with original v_f's.

Conclusion and Future Work: Under the uncertainties considered, ambient noise interferometry remains robust. The key goal of this research is solving the 'inverse' problem: Allowing an acceptable standard deviation of the velocity estimates, what are receiver positions in a multi-agent system that adhere to this constraint. Future work includes analytical derivation of uncertainty propagation and considering individual positional uncertainties of agents depending on the layout of the multi-agent system.

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