# ARES AND ARTEMIS: THE AUTONOMOUS ROVING EXPLORATION SYSTEM FOR ACTIVE SOURCE SEISMOLOGY ON THE MOON

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**Introduction:** NASA's Artemis program will enable a sustainable human presence on the Moon. A key objective of the program is to investigate water ice within regolith in the lunar south pole, which could provide fuel and life support. The origin and concentration of water ice in lunar regolith is not well understood. Determining the concentration of water ice at the surface and whether it persists with depth could help determine if the ice was delivered by comets or is endogenic [1].

We propose active seismic surveying to quantify regolith ice content at lunar south pole landing sites. The ice content in lunar regolith is likely correlated with seismic shear wave velocity. Seismic surface wave analysis of analog permafrost material on Earth has demonstrated that shear wave velocity increases dramatically with ice content [2, 3]. We suggest using surface wave analysis to measure ice content in near surface regolith on the Moon. Additionally, seismic refraction analysis would reveal subsurface layering within the near surface [4]. When seismic data are combined with ground truth measurements of ice content from near surface samples, a seismic survey could estimate the total ice content of an entire landing site.

ARES, the Autonomous Roving Exploration System [5], is a payload concept that could conduct active source seismic surveys on the Moon in conjunction with Artemis. It is natural that a return to the Moon would include a return to lunar seismic surveying. Active seismic surveying proved to be a valuable method to reveal regolith structure during the Apollo missions [6, 7]. As such, the measurement technology and processing methods to enable ARES already exist. We primarily consider ARES as a surveying tool to be launched before crewed Artemis missions. If launched prior to a manned mission, the system could provide a detailed survey of near surface lunar ice distribution for future resource utilization. However, ARES could also be deployed alongside crewed Artemis missions.

**Concept overview:** ARES requires multiple rovers to be delivered to the Lunar surface, a requirement that the Artemis Large-Scale Cargo Lander can support. One large rover would generate a seismic source, and two or more small rovers would act as seismic receivers (geophones). As depicted in Figure 1, the system acquires data by generating a seismic source and recording surface waves and refractions from subsurface structure at various locations offset from the source. Collecting data at far offsets from the source is necessary for observing refraction events and surface wave dispersion. A collection of autonomous source and receiver rovers provide configurability and redundancy to collect enough data to survey a landing site.

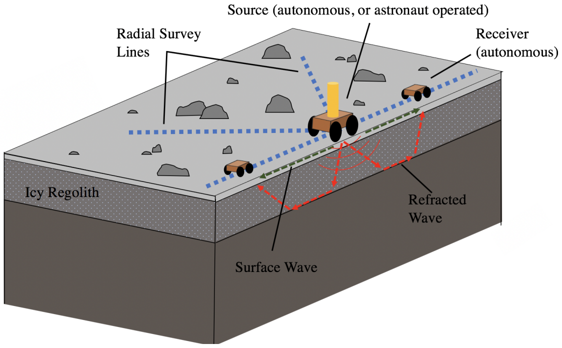

**Figure 1:** *The ARES concept illustrated over icy regolith layering on the Moon. Figure 4 shows a numerical simulation of this scenario.*

*Receivers:* For the receiver rover, we consider the small and nimble 10kg Resource Prospector rover produced by Lunar Outpost (Figure 2a). The Resource Prospector has the ability to autonomously navigate using advanced path finding techniques guided by cameras and LiDAR. Each receiver rover would have an attached geophone, like the one provided by Geophysical Technology Inc's (GTI) NuSeis NRU 1C nodal geophone (Figure 2b). These geophones could collect and wirelessly transmit data to the larger source rover or Artemis lander. Additionally, the small receiver rovers would operate on battery power and periodically rendezvous with the large rover to recharge if solar power is unavailable. Presuming the rover is adequately coupled with the surface, the geophone could sense seismic vibrations through the body of the rover without being directly inserted into the ground [8]. The receivers do not require direct control from astronauts, but could be teleoperated if desired.

**Figure 2:** *Existing systems for ARES's reciever rovers: (a) Lunar Outpost's 10kg Resource Prospector rover (https://www.lunaroutpost.com), and (b) GTI's NuSeis NRU 1C geophone (https://geophysicaltechnology.com).*

*Source:* If landed ahead of human missions, the source rover would contain critical systems like communication and power generation. To generate a seismic source, the rover would have an attached accelerated weight drop system. Accelerated weight drop systems are simple, robust, and repeatable. However, weight drop sources require significant mass. Although there are lighter sources such as dynamite, they are not repeatable, and thus could not complete a seismic survey. If operated by an astronaut, a simpler weight drop system without full roving capabilities could reduce total mass.

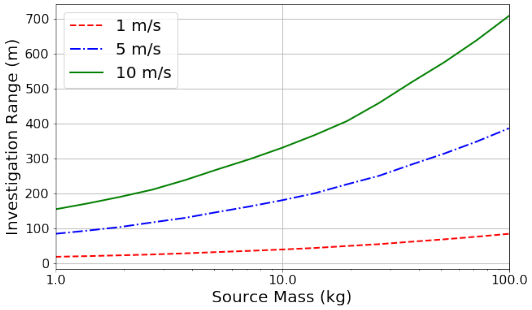

**Figure 3:** *Investigation depth/distance as a function of source mass and velocity assuming an impact seismic efficiency of* 10 $^{3}$*, a subsurface interface with a reflection coefficient of* 0.2*, a seismic quality factor of* 1000*, a receiver noise floor of* $< 0.5$ *µm/s, and a regolith with p-wave velocity of* 300 *m/s and density of* 1.5 *g/cc.*

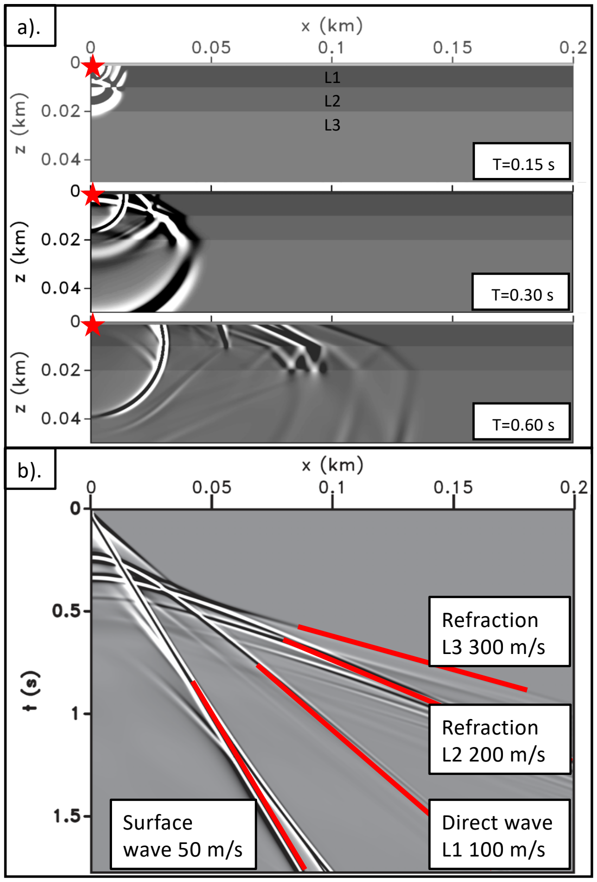

**Figure 4:** *(a) Wavefield snapshots for an elastic wave generated by an ARES source. (b) Synthetic seismic shot gather as would be collected by ARES receiver rovers.*

The required source weight depends on the desired survey size or investigation depth. Figure 3 demonstrates investigation depth/distance as a function of the weight drop's mass using methodology from [4, 9]. The maximum distance that a seismic wave can travel and still be detectable is dependent on the kinetic energy of the weight drop, the frequency of the source pulse, the seismic properties of the ground, and the noise floor of the geophones. The values in Figure 3 are consistent with values observed in terrestrial studies [10]. Provided the source mass' acceleration is assisted, the system would be indifferent to gravity. However, to prevent the rover from leaving the surface while accelerating the the mass, the rover as a whole would need to be heavier, perhaps by a factor of ten, than the weight itself.

**Numerical Modeling and Future Work:** Using numerical simulations, we demonstrate the ability of ARES to investigate lunar regolith properties. Figure 4 illustrates a surface wave and refraction events from synthetic elastic data acquired over a three layer lunar regolith model. Numerical methods can also predict the surface wave dispersion curve that ARES would observe over icy lunar regolith. Potentially, the ice content would have a drastic effect on the dispersion relation. Future modelling work will determine how sensitive the surface wave data would be to ice content.

**Conclusion:** We advocate for active source seismology to investigate ice content in lunar regolith at Artemis landing sites. Our proposed payload concept, ARES, could accomplish an active source seismic survey and would provide a powerful method for scientific investigation and resource surveying in advance of a sustained human presence on the Moon.

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