ARES: THE AUTONOMOUS ROVING EXPLORATION SYSTEM FOR ACTIVE SOURCE SEISMOLOGY ON THE MOON AND MARS S. W. Courville[1], N. E. Putzig[1], P. C. Sava[2], M. R. Perry[1,2], D. Mikesell[3], [1]Planetary Science Institute, Lakewood, CO. [2]Colorado School of Mines, Golden, CO. [3]Boise State University, Boise, ID. (swcourville@psi.edu)

Introduction: The Mars Exploration Program Analysis Group (MEPAG) recommends sending a resource prospecting mission to Mars in advance of human exploration [1]. High value subsurface martian resources include lava tubes, which provide a radiation shielded habitat, and buried water ice, which can provide fuel and life support [2, 3]. Similarly, lunar lava tubes could protect a long term human presence on the Moon. To enable human exploration and habitation of the Moon and Mars, the space exploration community needs the ability to survey these valuable subsurface targets with high accuracy and confidence prior to human arrival.

Concept overview: The Autonomous Roving Exploration System (ARES) is a payload concept designed to conduct active source seismic imaging [4]. Active source seismology originated early last century and is now a standard method for terrestrial resource exploration and subsurface imaging. Thus instrumentation and methodology are well developed. The challenge with applying active source seismology on the Moon and Mars is that the survey system must be autonomous.

ARES consists of multiple rovers: 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 reflections from a subsurface target at various locations offset from the source. Collecting data offset from the source is necessary to create images of subsurface structure and is superior to vertical sounding instruments. A collection of autonomous source and receiver rovers provide configurability and redundancy to collect enough reflection seismic data to create highly detailed images of the subsurface.

We propose the development of ARES to complement existing radar sounding systems. For the scenario depicted in Figure 1, orbital sounding radars like the Mars Reconnaissance Orbiter's Shallow Radar sounder do not have high enough resolution to detect the lava tube, and rover based ground penetrating radar would likely attenuate too quickly to reach it [5].

Receivers: Each receiver rover would have an attached geophone. 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. For the attached geophones, we consider Geophysical Technology Inc's (GTI) NuSeis NRU 1C nodal geophone (Figure 2b). These geophones would be able to collect and wirelessly transmit data to the larger source rover. Additionally, the small receiver rovers would operate on battery power and periodically rendezvous with the large rover to recharge. Presuming the rover is adequately coupled with the surface, the geophone would sense seismic vibrations through the body of the small rover without being directly inserted into the ground.

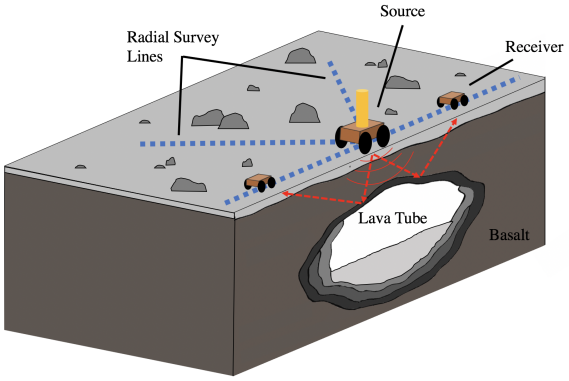

Figure 1: *The ARES concept illustrated over a lava tube. Figure 4 shows a numerical simulation of this scenario.*

Source: The larger 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.



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

We quantify the expected investigation depth of a weight drop source using theory developed by [6, 7]. The investigation depth is dependent on the kinetic energy of the weight drop, the frequency of the resulting source pulse, the seismic properties of the ground, and the noise floor of the geophones. For a weight drop system, the greater the mass and/or velocity of the weight, the more energy that is transferred into a seismic source, and thus the greater depth that can be seen. Additionally, the more sensitive the geophones are, the deeper the system can investigate. Figure 3 demonstrates investigation depth as a function of the weight drop's mass. The values in Figure 3 are consistent with values observed in terrestrial studies [8]. Note that the mass of the source rover as a whole would need to be several times heavier than the weight itself.

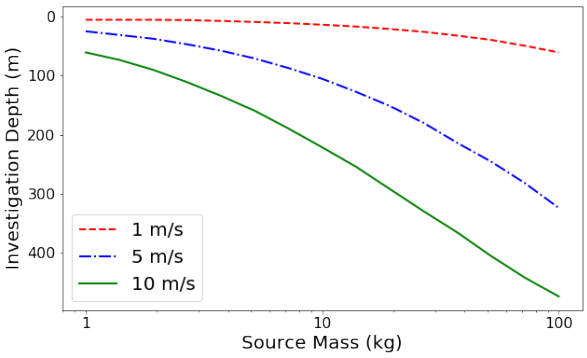

Figure 3: *Investigation depth as a function of source mass and velocity. These curves are valid for a regolith with a p-wave velocity of* 500 *m/s and a density of* 2 *g/cc; an impact seismic efficiency of* 10^{-3}*; a subsurface interface with a reflection coefficient of* 0.2*; a seismic quality factor of* 1000*; and a receiver noise floor of* < 1 *μm/s.*

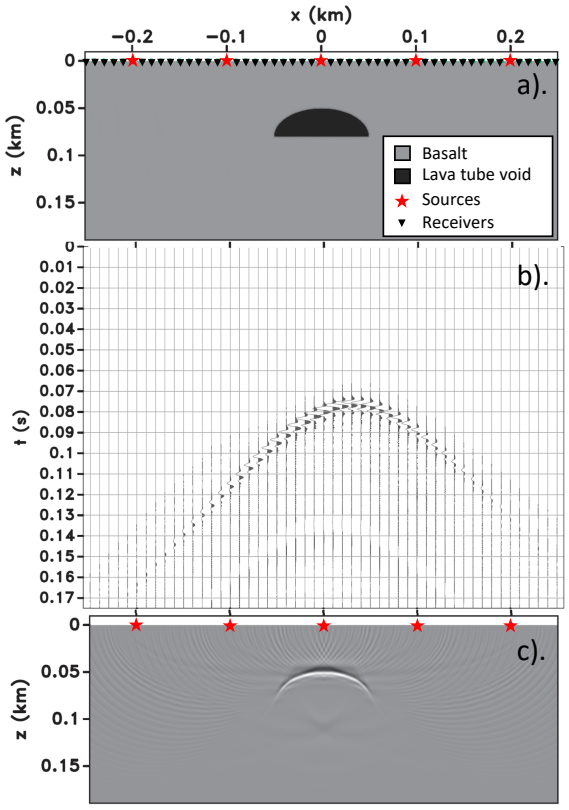

Figure 4: *(a) A simplified lava tube cross section model with a potential ARES 2D profile acquisition scenario. (b) synthetic seismic data shot gather for the source at x=0.1 km. (c) The subsurface image created through reverse time migration.*

Numerical modeling: Using numerical simulations, we demonstrate that ARES could image high value targets like lava tubes. Figure 4 illustrates a reverse time migration seismic image generated from simulated acoustic data acquired if the ARES system surveyed a 2D profile over a lava tube. The wavelength of the seismic source pulse in the medium determines the resolution of the image [9, 6].

Future work: We have submitted a Planetary Science and Technology Through Analog Research Program proposal to test the proposed ARES system over a lava tube on Earth. We will test whether geophones need to be pressed into the ground or if they can record adequate data on board the receiver rovers. Additionally, we will autonomously collect data over the extent of the lava tube and compare the resulting image with the known shape of the lava tube to address uncertainty.

Conclusion: We advocate for active source seismology to survey subsurface resources on bodies like the Moon and Mars. The ARES concept could accomplish an active source seismic survey and fill the surveying gap between near surface ground penetrating radar and orbital radar sounding. ARES would provide a powerful tool for resource surveying in advance of human exploration of Mars or long term habitation on the Moon.

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References [1] *MEPAG*, 2015. [2] P. J. Boston et al. In *AIP Conf. Proc.*, 2004. [3] A. Abbud-Madrid et al. *Report of the Mars Water In-Situ Resource Utilization (ISRU) Planning (M-WIP) Study*, 90, 2016. [4] S. W. Courville et al. *AGU Fall Meeting*, (P54D-02), 2018. [5] S. W. Courville et al. *AGU Fall Meeting*, (P44B-05), 2019. [6] K. Aki and P. G. Richards. *Quantitative seismology*. 2002. [7] M. A. Meschede et al. *Geophys. J. Int.*, 187(1):529–537, 2011. [8] R. D. Miller et al. *Geophysics*, 51(11):2067–2092, 1986. [9] A.J. Berkhout. *Seismic resolution*. Geophys. Press, 1984.