GEOPHYSICAL SCIENCE ON THE SURFACE OF THE MOON ENABLED BY ARTEMIS. N. Schmerr[1], J. Richardson[1,4], R. Ghent[2], M. Siegler[3], K. Young[4], M. Wasser[4], P. Whelley[1,4], D. Buczkowski[5], L. Carter[6], C. Connor[7], L. Connor[7], J. Bleacher[4], M. Fouch[8], D. Baker[4], T. Hurford[4], L. Jozwiak[5], S. Kruse[7], V. Lekic[1], A. Naids[10], R. Porter[11], L. Montesi[1], D. C. Richardson[1], E. Rumpf[12], N. Schorghofer[3], J. Sunshine[1], S. Goossens[4,18], N. Whelley[1,4], D. Wyrick[9], W. Zhu[1], E. Bell[1], J. DeMartini[1], D. Coan[10], D. Akin[1], B. Cohen[4], E. Mazarico[4], C. Neal[13], M. Panning[14], N. Petro[4], B. Strauss[4], R. Weber[15], T. Glotch[16], A. Hendrix[3], A. Parker[17], and S. Wright[3], [1]University of Maryland, College Park, MD, USA (nschmerr@umd.edu), [2]University of Toronto, Toronto, Canada, [3]Planetary Science Institute, Tucson, USA, [4]Goddard Space Flight Center, Greenbelt, USA, [5]Johns Hopkins Applied Physics Laboratory, Laurel, USA, [6]University of Arizona, Tucson, USA, [7]University of South Florida, Tampa, USA, [8]Samara/Data, Washington DC, USA, [9]Southwest Research Institute, San Antonio, USA, [10]NASA Johnson Space Center, Houston, USA, [11]Northern Arizona University, Flagstaff, USA, [12]USGS, Flagstaff, USA, [13]Univerity of Notre Dame, Notre Dame, USA, [14]Jet Propulsion Laboratory, Pasadena, USA, [15]NASA Marshall Space Flight Center, Huntsville, USA, [16]Stony Brook University, Stony Brook, USA, [17]Southwest Research Institute, Boulder, USA. [18]University of Maryland Baltimore County, USA.

Introduction: Geophysical methods have been incredibly successful in identifying resources on Earth as they provide a means of characterizing and mapping the sub-surface using data gathered on and above the target structures. **Geophysics on the Moon will be an important tool for identifying key targets for geological prospecting, scientific sampling, assessing hazards and risks to crew and infrastructure, and determining the near subsurface and deeper workings of the lunar interior.** Artemis will require 21st century geophysics instruments to advance lunar science and exploration, similar to how Apollo gathered geophysical data that is still leading to scientific discoveries 50 years later [e.g., 1].

Geophysics, which provides for the remote sensing of planetary interiors, has defined and imaged planet Earth's global structure with progressively increasing resolution since the early 20th century. Beginning in the 1960s, geophysics played a pivotal role in the development of plate-tectonic theory and has been central in identifying natural resources for our civilization. In the past, planetary science has been dominated by orbital or fly-by spacecraft, and therefore most of our geophysical information on extraterrestrial interiors comes from gravitational, magnetic, and electromagnetic fields. Until recently, landed missions have focused on geochemical analysis and geologic observations. However, the six US Apollo missions performed a host of geophysics experiments on the surface of the Moon, including passive and active seismology [2], heat flow [3], magnetometry [4], retroreflectors for lunar ranging [5], and surface gravity measurements [6]. More recently, the geophysical properties of the Moon were explored from orbit with the Gravity Recovery and Interior Laboratory (GRAIL) [7]. Since Apollo, the only ground-based geophysics were executed by China's Chang'e 3 and 4, which both acquired ground-penetrating radar (GPR) data from lunar rovers [1].

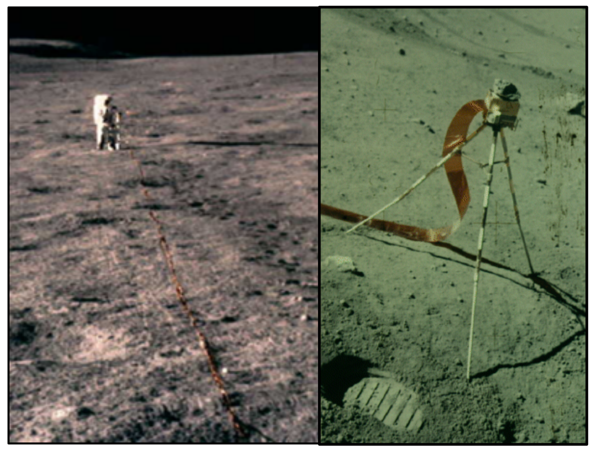

Figure 1. Left: Apollo 14 astronaut Edgar Mitchell operates the Thumper for the Active Seismic Experiment [2]. Right: The Lunar Portable Magnetometer of Apollo 16 [4]. These portable geophysics instruments are highly analogous to field geophysics instruments used in exploration on Earth and have provided some of the highest fidelity data to understand the shallow and deep subsurface at the Moon at length scales and resolutions inaccessible from orbital data.

From both orbit and the surface, geophysics has provided a tantalizing glimpse of the Moon's structure from crust to core [e.g., 1, 9], its internal temperature and global thermal evolution, as well as information on locations to prospect for possible in-situ resources. The Moon has served as a proven, comprehensive testbed for extraterrestrial geophysics, which has set the stage for surface geophysical experiments on other worlds, notably the Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) mission to Mars [10]. InSight successfully landed at Elysium Planitia on Mars in November 2018 and is now the first ground-based geophysics-focused mission in the Solar System. **Despite these advances, key geophysical questions remain unanswered about the near-surface resources of the Moon. Artemis and CLPS missions provide a new opportunity to**

investigate near surface and deep interior structure on the Moon.

As humans journey further into space, access to critical supplies needed to sustain themselves including food, air, water, shelter, rocket fuel, and spare parts will be essential. It is of paramount importance for future explorers to be able to efficiently identify and utilize resources found in the environments around them. Geophysics is a powerful tool for sounding the subsurface for the presence of potential *in situ* resource utilization (IRSU) materials and has been and remains essential for resource identification on Earth.

For the Moon, we identify four essential resources that will enable future human space exploration and ISRU that Artemis missions might investigate: I) Subsurface ice deposits, that can be used for volatile extraction; II) Regolith, which covers the surface of all target bodies, potentially serving as a building material but also presents a hazard to human and robotic operations and health; and III) Magma-tectonic Systems, which mobilize, concentrate, and trap volatiles, unique rocks, and ore minerals, and IV) Lava tubes and void spaces, capable of hosting people and infra-structure. These geophysical targets are available at many landing sites across the surface of the Moon that have been identified as high priority by the science community [11].

Geophysical Investigations within Artemis: **While single geophysics instruments are capable for specific non-destructive investigations of the subsurface, by integration of multiple geophysical methods will constrain subsurface structure.** The interpretation of geophysical methods is often non-unique or uncertain. This can be overcome by combining diverse methods that are sensitive to complementary material properties [12]. The combination of integrated field observations and process-based modeling links insights from Earth-based geophysical analogs to Artemis landing sites (**Figure 1**).

As a primary Artemis requirement is to investigate ice at the lunar south pole, multiple instruments working in collaboration can add fidelity to and expand prospecting. For example, while neutron spectrometers can detect ices in the shallowest meter in the subsurface, ground penetrating radars can connect such findings across measurement sites and to greater depths of multiple meters. Active source seismic soundings can provide details on the geotechnical properties of the regolith and complement the radar measurements [13-14]. **We recommend that an astronaut-led field campaign of geophysical measurements should be a key component of future Artemis science activities.**

Furthermore, to enable ISRU and lunar science, future crewed exploration of the lunar surface must include deployment of long-lived monitoring observatories (seismometers, heat flow experiments, retroreflectors, EM soundings, magnetometers, etc.), ideally deployed in networks across the surface of the Moon [15-18]. These would strongly complement any near-surface active geophysical surveys to characterize the detailed geological subsurface (ground penetrating radar, active source seismics, active EM soundings, magnetics [19], potential fields surveys). **Geophysical investigations can be carried out at Artemis sites if geophysics equipment is fundamentally portable to astronauts or related telerobotic operations, and further enabled deployment of long-lived lunar infrastructure** [20].

Future Outlook: The Artemis missions will serve as a comprehensive testbed for extraterrestrial geophysics by explicitly integrating across different existing datasets and by assessing the improvements to subsurface exploration and geological interpretation that would be enabled by human presence. Furthermore, interest and opportunities for the next generation of geophysical experiments on the Moon are at an all-time high, including forthcoming NASA partnerships with commercial missions deploying equipment on the lunar surface, and the New Frontiers competition in which the Lunar Geophysical Network is a strong candidate [21]. In depth geophysical exploration of landing sites by Artemis will extend findings of potential CLPS and LGN geophysical data that has limited portability. Artemis surface geophysics will also connect information acquired at orbit to the outcrop scale at the Lunar South Pole and beyond. Extending lessons learned from the human exploration of the Moon to near-Earth asteroids and the moons of Mars is also of interest, as astronaut exploration of these bodies will be complementary to a future human presence on Mars.

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