GEOPHYSICAL EXPLORATION OF THE DYNAMICS AND EVOLUTION OF THE SOLAR SYSTEM (GEODES). N. Schmerr1, J. Richardson1, R. Ghent2, M. Siegler3, K. Young3, M. Wasser4, P. Whelley1, D. Buczkowski5, L. Carter6, C. Connor7, L. Connor, J. Bleacher4, M. Fouch8, D. Baker4, T. Hurford8, L. Jozwiak8, S. Kruse9, V. Lekic1, A. Naids10, R. Porter11, L. Montesi1, D. C. Richardson1, E. Rumpf12, N. Schorghofer13, J. Sunshine1, S. Goossens4, N. Whelley1, D. Wyrick9, W. Zhu1, E. Bell4, J. DeMartini1, D. Coan10, D. Akin1, B. Cohen4, E. Mazarico4, C. Neal13, M. Panning14, N. Petro4, B. Strauss4, R. Weber15, T. Glotch16, A. Hendrix1, A. Parker1, and S. Wright1, 1University of Maryland, College Park, MD, USA (nscherrr@umd.edu), 2University of Toronto, Toronto, Canada, 3Planetary Science Institute, Tucson, USA, 4Goddard Space Flight Center, Greenbelt, USA, 5Johns Hopkins Applied Physics Laboratory, Laurel, USA, 6University of Arizona, Tucson, USA, 7University of South Florida, Tampa, USA, 8Samara/Data, Washington DC, USA, 9Southwest Research Institute, San Antonio, USA, 10NASA Johnson Space Center, Houston, USA, 11Northern Arizona University, Flagstaff, USA, 12USGS, Flagstaff, USA, 13Univeristy of Notre Dame, Notre Dame, USA, 14Jet Propulsion Laboratory, Pasadena, USA, 15NASA Marshall Space Flight Center, Huntsville, USA, 16Stony Brook University, Stony Brook, USA, 17Southwest Research Institute, Boulder, USA. 18University of Maryland Baltimore County, USA.

Introduction: The Moon, near-Earth asteroids, and the martian moons Phobos and Deimos are all Solar System Exploration Research Virtual Institute (SSERVI) target bodies as they present a wide variety of natural wonders and are potential hosts to in situ resources that will one day enable human exploration of the Solar System. Our SSERVI project, Geophysical Exploration of the Dynamics and Evolution of the Solar System (GEODES) is exploring a suite of natural geophysical resources on these bodies through multidisciplinary geophysical investigations.

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. We focus our geophysical investigations on four essential resources that will enable future human space exploration and in situ resource utilization (IRSU): I) Lava tubes and void spaces, capable of hosting people and infra-structure; II) Subsurface ice deposits, that can be used for volatile extraction; III) Regolith, which covers the surface of all target bodies, potentially serving as a building material but also presenting a hazard to human and robotic operations and health; and IV) Magma-tectonic Systems, which mobilize, concentrate, and trap volatiles, unique rocks, and ore minerals. Examples of each topic under these themes can be found in Figure 1.

Geophysics, as the remote sensing of planetary interiors, has defined and imaged planet Earth’s global structure, from crust to core, 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. Because planetary science has been dominated by orbital or fly-by spacecraft, most of our geophysical information on extraterrestrial interiors comes from gravitational, magnetic, and electromagnetic fields. However, six US Apollo missions performed a host of geophysics experiments on the surface of the Moon, including passive and active seismology [1], heat flow [2], magnetometry [3], retroreflectors for lunar ranging [4], and surface gravity measurements [5]. More recently, the geophysical properties of the Moon were explored with the Gravity Recovery and Interior Laboratory (GRAIL) [6]. 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 [7]. From both orbit and the surface, geophysics has provided a tantalizing glimpse of the Moon’s structure from crust to core [e.g., 8, 9], as well as information on its internal temperature and global thermal evolution. 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.

Figure 1. GEODES investigations explore four Resource Themes that are critical to 21st century geophysical exploration of the Moon, NEAs and the moons of Mars, informed by analog sites in the western United States (see inset map).
InSight successfully landed at Elysium Planitia on Mars in November 2018 and is now the first ground-based, and geophysics-focused mission in the Solar System. Despite these advances, key geophysical questions remain unanswered about the near-surface resources of the Moon, and much less is known about asteroids and the moons of Mars.

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 ISRU materials and has been and remains essential for resource identification on Earth.

**Approach:** GEODES aims to provide maximum insight by integrating multiple geophysical methods together. 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 [11]. The combination of integrated observations and process-based modeling allows GEODES to link insights from Earth-based geophysical analogs to the environments present beyond Earth (Figure 2), and also to develop best practices for future geophysics exploration of ISRU targets.

**Analog Sites:** Our team has identified three field sites that provide access and opportunities to: 1) validate models of near-surface structure in analog geologic settings (e.g., lava flows, lava tubes, cinder cones), 2) test data collection methods in order to develop instrument and mission architecture recommendations, 3) determine the optimal scales of measurements to characterize resources, and 4) identify the observational overlap between outcrop-scale and orbital geophysical measurements. Upcoming 2020-2025 GEODES field expeditions will be to Lava Beds National Monument, northern California, the San Francisco Volcanic Field (SFVF), Flagstaff, Arizona, and the East Snake River Plain, southern Idaho, and targets in Hawaii and Iceland.

**Geophysical Methods:** In this context the goal of GEODES is to develop geophysical detection and exploration methods to characterize these natural resources and enable ISRU at SSERVI target bodies. Our team is addressing this goal by developing workflows that create geologically consistent exploration strategies, integrate geophysical models to reduce uncertainty, and test geophysical models for specific resource targets, including lava tubes and void spaces, ice deposits, regolith, and magma-tectonic environments. Our strategy incorporates geological model development, existing planetary data, and new data from analog field investigations. GEODES will serve the exploration community by expanding the capacity to facilitate ISRU at SSERVI target bodies.

**Future Outlook:** The Moon will serve as a comprehensive testbed for extraterrestrial geophysics by explicitly integrating across different existing datasets and by assessing the improvements to subsurface remote sensing 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 [12].Extending lessons learned from the Moon to near-Earth asteroids and the moons of Mars is also of interest, as astronaut exploration of these bodies will provide steppingstones for a human presence on Mars.