TRANSFORMATIVE SCIENCE ON THE MOON USING TETHERED DISTRIBUTED SENSORS WITH ASTRONAUT-ASSISTED DEPLOYMENT AT ARTEMIS LANDING SITES. J. O. Burns[1], A. Austin[2], S. D. Bale[3], J. Bowman[4], R. F. Bradley[5], T-C. Chang[2], S. Furlanetto[6], G. Hallinan[7], M. Hart[2], A. Hegedus[8], M. Klein Wolt[13], J. Lux[2], N. Mahesh[7], J. Mirocha[2], B. Nhan[5], J. Pober[9], R. Polidan[10], D. Rapetti[11,1], A. Slosar[12], S. Squyres[14], M. Smith[2], L. Teitelbaum[2], Z. Zhan[7]. [1]University of Colorado, Boulder, CO (jack.burns@colorado.edu), [2]JPL/Caltech, Pasadena, CA, [3]SSL, University of California, Berkeley, CA, [4]Arizona State University, Tempe, AZ, [5]NRAO, Charlottesville, VA, [6]UCLA, Los Angeles, CA, [7]Caltech, Pasadena, CA, [8]SRI International, Ann Arbor, MI, [9]Brown University, Providence, RI, [10]Lunar Resources, Houston, TX, [11]USRA, NASA Ames Research Center, Moffett Field, CA, [12]DOE Brookhaven National Lab, Upton, NY, [13]Radboud University, Nijmegen, The Netherlands, [14]Blue Origin, Kent, WA.

Introduction: Distributed arrays of surface sensors deployed by astronauts at Artemis landing sites have the potential to address multiple science goals identified in the Artemis Science Plan and the Artemis III Science Definition Team Report (SDT). These include geophysical measurements of the deep lunar interior via seismology, Earth-observing studies from the unique platform of the Moon, heliophysics investigations from the lunar surface, and viewing the Universe and seeds of galaxy structure in the unexplored "Dark Ages". Here we describe a simple method to deploy optical and radio sensors via flat tape tethers (Fig. 1) over ≈km baselines unspooled by astronauts using a straight-forward roller. The Artemis landing sites at the lunar south pole are ideal for a tether technology demonstration and science investigations given the likely terrain free of large boulders and with slopes <5º. This concept does not require direct Earth communications and would benefit from locating on a crater rim with long duration sunlight for power. It would be helpful to have some shielding from radio interference for the Dark Ages science.

Distributed Fiber Seismic Sensing: Tectonic activity and internal structure of planets/moons are fundamental to understanding their formation, evolution, and habitability. The Moon is of particular interest, due to its close relation with the Earth. Four seismometers deployed during the Apollo missions provided fundamental constraints on the Moon's activity and structure [1,2]. However, outstanding scientific questions, such as the hemispherical difference in crust and mantle structure, seismic activity beyond the lunar near side, and the nature of core-mantle boundary remain unresolved. Answering these questions requires more seismometers and dense seismic arrays. Constrained by technical difficulties and cost, planetary seismology has mostly been focusing on single devices (e.g., Mars *InSight*) or a few stations (e.g., Apollo, Lunar Geophysical Network).

As part of the design study for the FARSIDE radio array [3,4], we developed a concept to deploy hundreds of radio dipole antennas as well as power and communications via optical fibers all embedded within flat ribbon tethers. For the Artemis Tethered array, the optical fibers can also be passively used for the deployment of a 1-km aperture, ≈1000-sensor seismological observatory. The Distributed Acoustic Sensing (DAS) technology can turn every meter of a km long optical fiber into a seismic sensor, by attaching an interrogation unit to one end of the fiber [5]. DAS works by shining a laser pulse into the fiber from one end and interrogating the "echo" of Rayleigh scattering from intrinsic fiber defects. If a fiber section is strained, the relative positions of the fiber defects within the section will change, and so will the corresponding backscattering, in both amplitude and phase. DAS measures the changes at a high sampling rate (e.g., 10 kHz) and converts them to strain measurements. The technology has proven to work well on Earth with either dedicated fiber optic cables or existing telecom fibers, without interfering data transfer over other strands of fiber in the same cable.

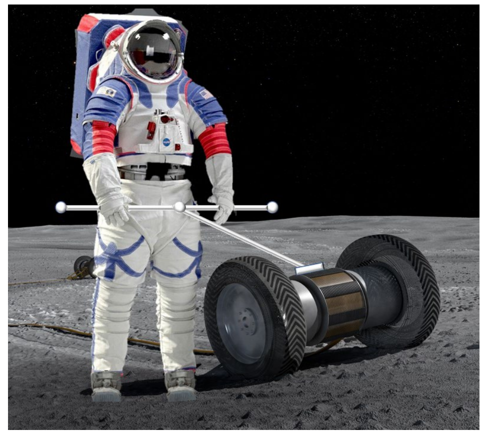

Figure 1: Illustration of Artemis astronaut-assisted deployment of flat tape tether with embedded optical fiber along with radio antennas and preamp nodes. The tether width is 1.4 cm, and the thickness is 1 mm, similar to that used by the Apollo ALSEP experiment.

Low Frequency Radio Interferometric Array: An astronaut-deployed tethered array of thin-wire radio dipole antennas operating at radio frequencies that are challenging or impossible from the Earth (~0.2-40

MHz), due to anthropogenic noise and a refractive and opaque ionosphere, opens a new window for radio science from the Moon. With a ≈km length tether unfurled in an L or spiral pattern, about a hundred 10-m tip-to-tip dipoles can be deployed to create a unique and sensitive synthetic aperture radio interferometer. With this array, new lunar science, heliophysics, and astrophysics will be enabled [6].

Sounding of the Lunar Subsurface: A tethered radio array has the potential to sound the mega-regolith and its transition to bedrock expected at ~2 km below the surface [7]. The Lunar Radar Sounder (LRS) onboard the SELENE spacecraft has provided sounding observations of the lunar highlands and found potential scatterers in hundreds of meters below the subsurface. However, the results are inconclusive due to surface roughness. An Artemis landing site radio array, by virtue of being on the surface, would not be affected by roughness. Data from a calibration beacon on the surface could be synthesized to identify deep scatterers and the transition to bedrock at km depths by virtue of the low frequencies, which are significantly more penetrating [see 8].

The Earth as an Exoplanet: As noted by the SDT, *the Moon offers a unique vantage point for full-disk observations that can help advance investigations of Earth as an exoplanet, focusing on key signatures of life to enhance current terrestrial exoplanet observation and characterization methods from ground-based and space-based observatories*. Low radio frequency interferometric imaging observations of the Earth serve as the prototype for investigations of stellar weather and magnetospheres for habitable exoplanets in the solar neighborhood. Stellar coronal mass ejections (CME) in exoplanet systems and the resulting energetic particle events are illustrated nearby by the Sun and the Earth. Further understanding the dynamic nature of the Earth's auroral kilometric radio emission via interferometric observations from the Moon will lay the groundwork for the detection of magnetospheres and their impact on habitability in nearby exoplanet systems.

Heliophysics Observations with a Tethered Radio Array: During the solar illumination of a lunar day, an Artemis tethered radio array will observe solar radio bursts, which are one of the primary remote signatures of electron acceleration in the inner heliosphere. Type II radio bursts originate from suprathermal electrons (E > 100 eV) produced at shocks. These shocks are generally produced by CMEs as they expand into the heliosphere with Mach numbers greater than unity. Emission from a Type II burst drops slowly in frequency as the shock moves away from the Sun into lower density regions at speeds of 400–2000 km/sec. Type III bursts are generated by fast (2–20 keV) electrons from magnetic reconnection, typically due to solar flares. As the fast electrons escape at a significant fraction of the speed of light into the heliosphere along open magnetic field lines, they produce emission that drops rapidly in frequency. Imaging the larger scales of structure in these bursts as they expand from the Sun, complementing the higher resolution imaging with SunRISE [9], would be enabled by a low frequency ≈km baseline array on the Moon.

The Early Universe's Dark Ages: The Astro2020 Decadal Survey stated that redshifted *21 cm line intensity mapping of the Dark Ages [is] both the discovery area for the next decade and [is] the likely future technique for measuring the initial conditions of the universe in the decades to follow.* The 21-cm wavelength radio radiation arises from neutral hydrogen that fills the Universe during this unexplored epoch, stretched via the expansion of spacetime to an observed wavelength of 10's of meters (10's of MHz). Spatial fluctuations in the 21-cm absorption during the cosmic Dark Ages provide the ultimate cosmological observable. The power spectrum characterizes the amplitude of the variations as a function of spatial scale. During this time, the 21-cm line traces the cosmic density field with most modes in the linear regime, allowing a straightforward interpretation of the measurement in terms of the fundamental parameters of our Universe [10]. The lack of luminous astrophysical sources makes the Dark Ages signal a clean and powerful cosmological probe and renders the 21-cm line the *only* electromagnetic observable signal from this era. An Artemis tethered array is an invaluable pathfinder for a larger 21- cm power spectrum instrument. It can both measure the intrinsic spectrum of the low-frequency foregrounds without the effects of the Earth's ionosphere and can be used as a testbed for foreground removal techniques.

Acknowledgments: This work is directly supported by the NASA Solar System Exploration Virtual Research Institute cooperative agreement 80ARC017M0006.

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