Executive Summary

The Network for Exploration and Space Science (NESS) team led by P.I. Jack Burns at the University of Colorado Boulder is an interdisciplinary effort to design and deploy low frequency radio telescopes on the lunar surface. These radio telescopes will make cosmological and astrophysical measurements of neutral hydrogen at the end of the Dark Ages, during Cosmic Dawn, and at the onset of the Epoch of Reionization, as well as measure the radio emission from the Sun and extrasolar space weather around exoplanets. NESS continues to advance instrumentation and a data analysis pipeline for the study of the first luminous objects (first stars, galaxies and black holes) and departures from the standard model of cosmology in the early Universe, using low frequency radio telescopes. The design of an array of radio antennas at the lunar farside to investigate the Dark Ages, Heliophysics, and Exoplanet Magnetospheres, is a core activity within NESS, as well as the continuous research of theoretical and observational aspects of these subjects. NESS is developing designs and operational techniques for teleoperation of rovers on the Moon's surface. New experiments, using rovers plus robotic arms and Virtual/Augmented Reality simulations, are being performed to guide the development of deployment strategies for low frequency radio antennas via telerobotics. Research supported by NESS has led to two NASA-funded CLPS missions that are scheduled to deploy the first U.S. radio telescopes on the Moon in mid-2023 (lunar south pole) and in 2024/2025 (lunar farside). For outreach, NESS published a website to explain Cosmic Dawn and Dark Ages to a general audience, and completed a SSERVI-funded, feature-length, full-dome planetarium film entitled "*Forward! To the Moon*" with over 0.5 million views from nearly 300 planetariums/museums. This year was mostly a no-cost extension for NESS devoted to completing remaining tasks rather than beginning new projects.

1. NESS Team Project Report

1.1. Primordial Hydrogen Cosmology from the Moon's Far Side

One of the principal goals of our collaboration is to study how low-frequency radio telescopes in the lunar environment will reveal the earliest phases of the Universe's history to learn about exotic physics (such as dark matter and primordial black holes) and the formation of the first stars, black holes, and galaxies. The best method to do this is with the "spin-flip" transition of neutral hydrogen, which pervades the early Universe and is sensitive to its properties on large scales. The lunar environment is an ideal platform for these efforts because it is free of terrestrial (human and ionospheric) interference.

1.1.1. Warm Dark Matter and the Global 21-cm Signal

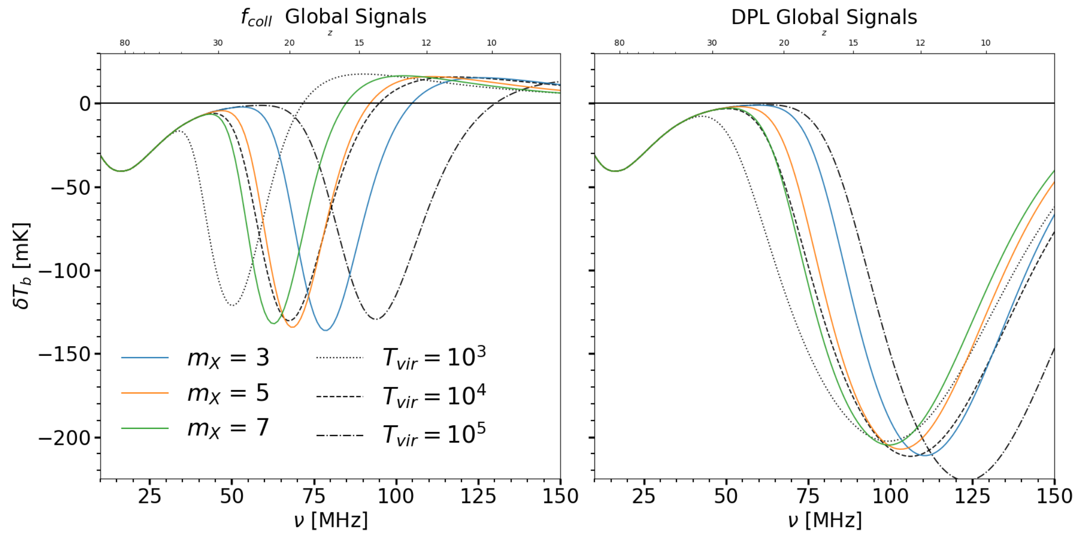

Figure 1: *Simulations of the global 21-cm signal at Cosmic Dawn when including the effects of Warm Dark Matter (see Hibbard et al. 2022). The black lines show the comparable cases for Cold Dark Matter when varying the virial temperature of the collapsed dark matter halos, while the colored lines show the effects of making Dark Matter warm. The left panel shows a star-formation model which is dependent only on the total collapsed fraction of Dark Matter, while the right panel shows a model where star-formation is strongly dependent upon halo mass.*

The global 21-cm signal provides a perfect testbed for constraining the nature of Dark Matter (DM). This is because DM constrains the number of halos in the universe, which in turn controls how many galaxies and stars collapse and release photons into the intergalactic medium (IGM). Traditionally, DM is modeled as “cold,” meaning that there is no cutoff in the number of low-mass DM halos in the Universe. In this work, we tested the case where DM is “warm,” with high streaming velocities that cause the smallest halos to disperse, ultimately impacting the number of star-forming halos and the number of photons which are released into the IGM.

Figure 1 shows the global 21-cm signal for two different star-formation parametrizations (right versus left panel – in the left, sources only depend upon the total amount of collapsed DM, while in the right sources are a strong function of the halo mass). The colored solid lines show how the signal changes with various WDM masses (with higher mass leading to less free-streaming and thus less structure dampening), while the black dotted, dashed, and dot-dashed lines show the global signals for CDM with different minimum DM halo virial temperatures. Note that as mX → 10 keV, WDM → CDM. This research was published in the *Astrophysical Journal* led by CU graduate student Joshua Hibbard (Hibbard et al. 2022, ApJ 929, 151).

1.1.2. Theoretical Predictions of the Global 21-cm Signal and Synergy with JWST Observations

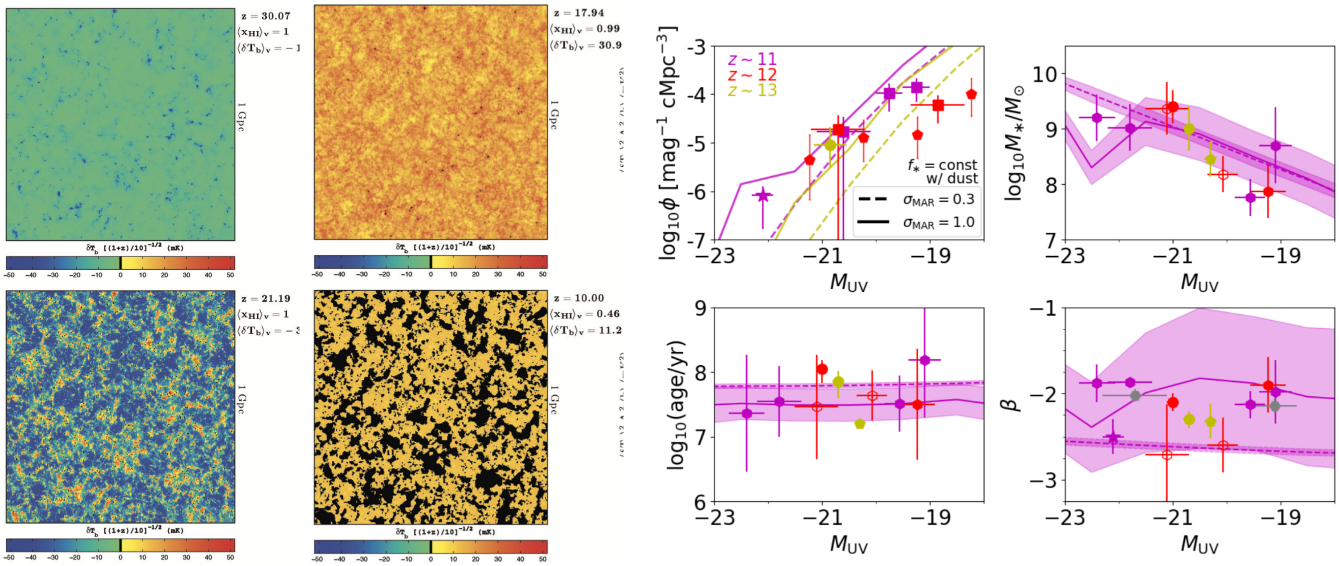

Figure 2: Simulations and model predictions of the effects of stochastic and dust extinction in various models. The left panels (moving from upper left to upper right to lower left to lower right) show simulations of the 21-cm signal evolving from before Cosmic Dawn through the Epoch of Reionization (Mesinger et al. 2011). The right panel shows the model predictions of galaxy properties, based upon data from JWST and various galaxy model assumptions (Mirocha & Furlanetto 2023).

Lunar radio telescopes hope to observe the spin-flip radio background from intergalactic hydrogen during the Cosmic Dawn. This signal evolves rapidly as the first luminous sources appear. The panels on the left in Figure 2 (from Mesinger et al. 2011) show four phases of this signal, from very early times (upper left), through the appearance of the first stars (lower left) and black holes (upper right) to reionization (lower right).

The timing of these eras depends on the growth of the first galaxies, now being measured by JWST. Mirocha & Furlanetto (2023) examined the implications of the first wave of galaxy candidates for early star formation. The right panel of plots shows a comparison of model predictions to inferred galaxy properties at z>11 (in the first 400 Myr of the Universe's history). In each panel, the points show observed galaxies, while the curves and shaded regions show our model results. The four panels show, clockwise from top left, the galaxy abundance, stellar mass, ultraviolet color, and inferred age. To match the observations, models require significantly elevated mean star formation efficiencies, surprising scatter between galaxies, and the presence of dust. If confirmed, the increased star formation will move the spin-flip signal to earlier times, making a lunar radio telescope even more important.

1.1.3. Instrument Development

1.1.3.1. FARSIDE Concept Instrumentation

The previously identified science of the FARSIDE mission (Burns et al. 2019a, 2021a) is wide-ranging, multidisciplinary, and reflects priorities from the Heliophysics, Planetary, and Astrophysics Decadal Surveys including (a) high dynamic range imaging of solar Type II radio bursts associated with shocks from Coronal Mass Ejections (CMEs) at >2 solar radii; (b) observations at <10 MHz of the outer planets (and Ganymede) to enable monitoring of the variable solar wind's impact on the auroral flux density and atmospheric lightning; (c) detection of the brightest Type II/III radio bursts from nearby stars with exoplanets out to 10 pc; (d) potential detection of terrestrial planet magnetospheres (which increases the odds of habitability) in nearby exoplanets via coherent radio emission at <1 MHz; (e) measuring the 3D matter power spectrum of the Cosmic Dawn to constrain cosmology and new physics (e.g., warm dark matter); and (f) sounding the mega-regolith on the Moon and its transition to bedrock expected at 2 km below the surface using a calibration beacon in orbit.

Several preliminary numerical simulations of the FARSIDE array design, u-v coverage, beam models, and simulated maps have since been undertaken. Hegedus et al. (2020) has developed an initial code to simulate arrays with different distributions of antennas on the lunar surface using LRO LOLA data. As a first test of this code, Figure 3 shows imaging of a Type II solar radio burst using FARSIDE. The model emission was obtained by taking a subset of data from an MHD re-creation of the CME observed on 5/13/2005 (see Burns et al. 2021a).

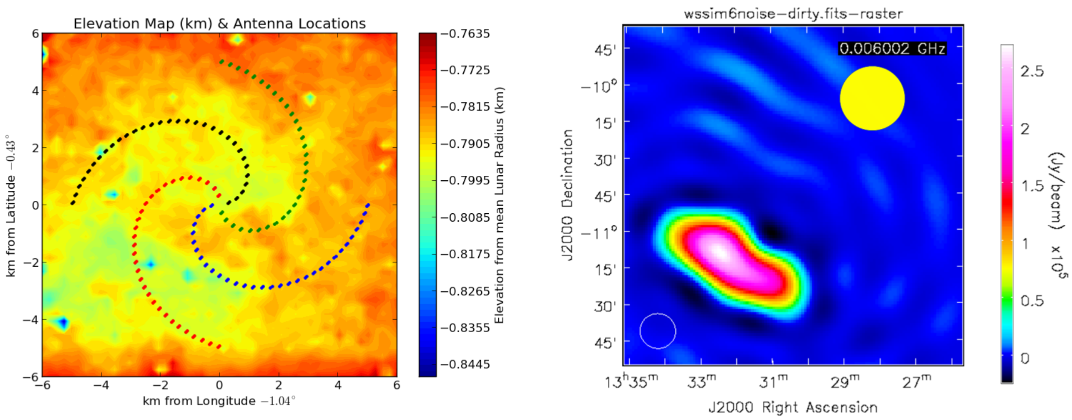

Figure 3: The spiral pattern of FARSIDE antennas produces an excellent synthetic aperture (good u-v coverage) and mapping of extended radio sources such as CMEs. Left: Distribution of antennas on the lunar surface with elevations derived from LRO LOLA. Right: Deconvolved radio map of Type II burst as imaged by the array at 6 MHz with 1 minute integration. The yellow circle is the Sun's disk, & the white circle is the beam FWHM.

The NESS team published the results of a robotic deployment study using single-axis rovers for FARSIDE in an IEEE Aerospace Conference Proceedings (McGary et al. 2022, https://arxiv.org/abs/2209.02216). The team also worked on developing concepts for prototype array deployments on the lunar surface within the context of PRISM and Artemis missions. These early missions will buy-down risk for FARSIDE and provide early science related to foregrounds for 21-cm cosmology and solar radio bursts.

1.1.3.2. Development of CLPS Missions: ROLSES and LuSEE Instrumentation

The Radiowave Observations at the Lunar Surface of the Electron Sheath (ROLSES) experiment was selected through NASA's CLPS program and will launch in mid-2023 on the Intuitive Machines IM-1 NOVA-C lander, recording spectra from 5 kHz to 30 MHz (see Figure 4). In the case of ROLSES, the Galaxy will move across the field-of-view of the instrument over the 8-10-day mission lifetime, providing information about the spatial distribution of the low frequency sky. We anticipate having 8 hrs of observations after sunset before the batteries on the lander are exhausted which will produce key data on dust levitation and night-time ambient noise levels. NESS team member B. Nhan performed numerical simulations of the ROLSES antenna beams to investigate how the electromagnetic properties of the lunar soil may influence the antenna response. These simulations employed CST Microwave Studio software, a commonly used tool for performing electromagnetic simulations, and found that the soil dielectric constant plays a much larger role in the instrument response compared to the loss tangent. CU graduate student Neil Bassett developed a Bayesian inference, forward-modeling code using training sets of sky, beam, and subsurface dielectric constants that will be used to extract parameters from the ROLSES data set using nested sampling algorithms.

The Lunar Surface Electromagnetics Experiment (LuSEE) is composed of two separate instruments on two separate landers to the lunar farside, LuSEE-Light and LuSEE-Night. The LuSEE-Night instrument will record observations from the lunar farside through multiple lunar day/night cycles (Bale et al. 2023, https://arxiv.org/abs/2301.10345). With the addition of the DOE as a partner for LuSEE-Night, we have sufficient funds to develop the antenna system, spectrometer, and batteries for operation during the lunar night. Thus, LuSEE-Night will make the first observations from the Moon within the bands corresponding to Cosmic Dawn and the Dark Ages and aims to set limits on the characteristics of the universe in these unexplored epochs. Similar to ROLSES, NESS team members also performed numerical simulations of the antenna response for the LuSEE instrument. In addition to investigating the effect of soil properties, NESS team members B. Nhan and N. Bassett collaborated with other members of the LuSEE-Night team to simulate varying antenna models (including length, placement, angle, etc.) in order to determine the optimal configuration to reduce antenna beam chromaticity. In addition, NESS and LuSEE-Night team members also compared the results from several different simulation software packages (including CST, FEKO, and HFSS) to ensure that each software package produced consistent results.

Figure 4: *The CLPS IM-1 NOVA-C lander will carry the ROLSES low radio frequency payload to the South Pole in 2023 setting the stage for subsequent CLPS Dark Ages 21-cm observations in 2025. Measurements will include the surface plasma sheath and lofted dust, the lunar subsurface, and the Galactic foreground. Credit: Intuitive Machines.*

1.1.3.3. Lunar Radio Instruments and Prototyping

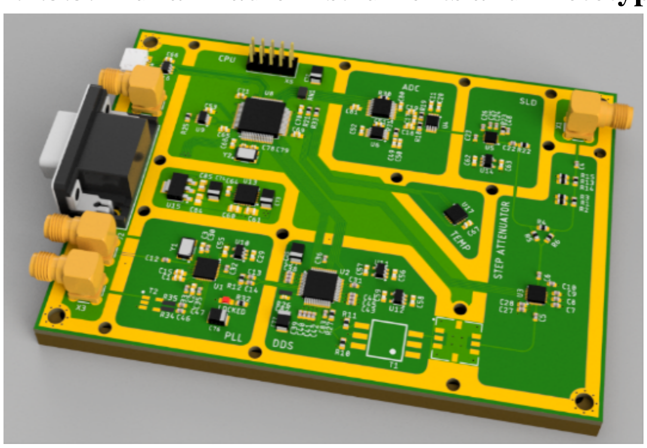

Figure 5: *Prototyping using ground-based telescopes will advance the design of lunar radio instruments. Shown here is a rendering of the prototype pilot tone gain tracking system developed by U. Virginia graduate students under guidance from Bradley (NRAO) and supported by SSERVI.*

Systematics imposed by the lunar environment impact the calibration and long-term stability of the instrument. Physical influences, such as the vertical profile and dielectric properties of the regolith, surface and subsurface temperature profiles and variability, dust size, density, and electrostatic properties, need to be studied to understand how these will affect the electromagnetic response of the antenna.

Towards that end, laboratory-based prototyping plays a significant role in developing component models that track circuit behavior accurately over a range of environmental conditions. For example, during the past year, Bradley's NRAO team has been investigating tone-based gain and antenna reflection coefficient tracking systems (early board design shown in Fig. 5) along with advanced correlation receivers. This allows us to study long-term stability and accuracy, and make comparisons with the science requirements for hydrogen cosmology measurements.

1.1.3.4. Ground-Based Telescope Analogs for Lunar Missions: CTP, EDGES, and OVRO-LWA

CTP is an engineering test instrument developed to evaluate antennas, radio receivers, data acquisition systems, and signal processing techniques for hydrogen cosmology measurements. Dynamic polarimetry, an important technique to aid in separating the sky foreground spectrum from that of neutral hydrogen, was demonstrated using two unique CTP configurations. During the past year, a precision, dual polarization, correlation receiver, based on the CTP, has been developed for use on the Green Bank Telescope to measure the absolute radio sky brightness at 310 MHz (Bordenave et al. 2021, 2022). This receiver will be used to refine the dynamic polarimetry method, provide calibrated data to exercise the pylinex data pipeline (Tauscher et al. 2018, 2020, 2021; Rapetti et al. 2020), and produce a high spatial resolution polarized sky map at this frequency to be used for lunar-based telescopes.

Over the last decade, the EDGES experiment has demonstrated key techniques to enable hydrogen cosmology measurements. It pioneered an electrically compact radio spectrometer design with a low-chromaticity broad-band antenna, embedded noise comparison, and absolute laboratory calibration. The experiment has operated four instruments in Western Australia, where it revealed a broad feature near 78 MHz that lies within the Cosmic Dawn band and set a lower limit on the duration of reionization at $\Delta z > 1$. In the last year, members of the EDGES collaboration and of the NESS team S. Murray and N. Mahesh developed a new, open-source analysis pipeline for EDGES called the "edges-collab pipeline" (based on the Github organization name under which it is hosted). It covers all analysis from data formatting and I/O through calibration to flagging, averaging, and parameter estimation. It is open-source and accessible to anyone that wishes to work with the EDGES data. It is also designed to be generic and usable for any single-antenna (or single-dish) global 21-cm experiment. The new pipeline has been tested with the data released in Bowman et al. (2018), and successfully produced results (residuals and cosmological parameter estimates) to within one sigma.

The primary development goal for the pipeline was to provide modularity and enable full traceability. Thus, the pipeline is currently being used to test the sensitivity of estimated cosmological parameters to various calibration and data processing choices. In Oct 2022, the EDGES team made the initial deployment of the upgraded EDGES system (v.3) with an improved receiver system and a larger ground plane. We will use the new EDGES pipeline on the data from the recently deployed EDGES-3 system. This past year, three scientific papers were published from the EDGES collaboration: 1) a Bayesian framework for joint-analysis of the receiver calibration, foregrounds, and 21-cm signal for the EDGES system (Murray, S. G., "A Bayesian calibration framework for EDGES," *Monthly Notices of the Royal Astronomical Society*, vol. 517, no. 2, pp. 2264–2284, 2022.); 2) a new mathematical formalism to accurately account for the spectral structure induced into the spectrometer data by the chromaticity of the beam ("A Bayesian approach to modeling spectrometer data chromaticity corrected using beam factors -- I. Mathematical formalism," *accepted into MNRAS*, 2022); 3) Analytically quantifying the effects of scattering from near objects on the data collected by the EDGES experiment (Rogers, A. E. E., "Analytic Approximations of Scattering Effects on Beam Chromaticity in 21-cm Global Experiments," *Radio Science*, vol. 57, no. 12, 2022).

The Owens Valley Radio Observatory Long Wavelength Array (OVRO-LWA) is a 352-antenna array capable of imaging the entire viewable sky below 85 MHz with a spatial resolution of ~9 arcmin at 80 MHz. OVRO-LWA will use all-sky images with 10-sec time resolution for near-continuous monitoring of the nearest 4000 known stellar/planetary systems to search for magnetospheric radio emission from exoplanets. The same data will be searched for the transient radio signatures of coronal mass ejections (CMEs) and energetic particle events, as well as preparing to observe the 21-cm power spectrum in the Cosmic Dawn epoch. In the past year, the entire OVRO collaboration has been actively involved in the commissioning efforts to make the array science ready. The team has successfully completed various sprint testing including digital beamforming tests, RFI tests to set flagging and attenuation algorithms, and monitor & control point tests for continuously accessing the health of the array. The OVRO group also brought together a team of postdocs and research scientists to plan for measurements and modeling of the element and array beam of OVRO-LWA. The team has put together an initial plan that involves carrying out a few electromagnetic simulations of the individual elements with varying environmental conditions, measurements of the antenna S11, and a few far field measurements using drones. All these efforts will inform beam requirements for the two primary science cases of the OVRO-LWA, i.e., exoplanet studies and 21-cm cosmology. The OVRO-LWA framework will serve as the basis of the future FARSIDE array. Thus, the commissioning and beam mapping efforts are paving the way for the future lunar mission.

1.2 The SunRISE Heliophysics CubeSat Array as a Prototype for a Lunar Far Side Interferometer

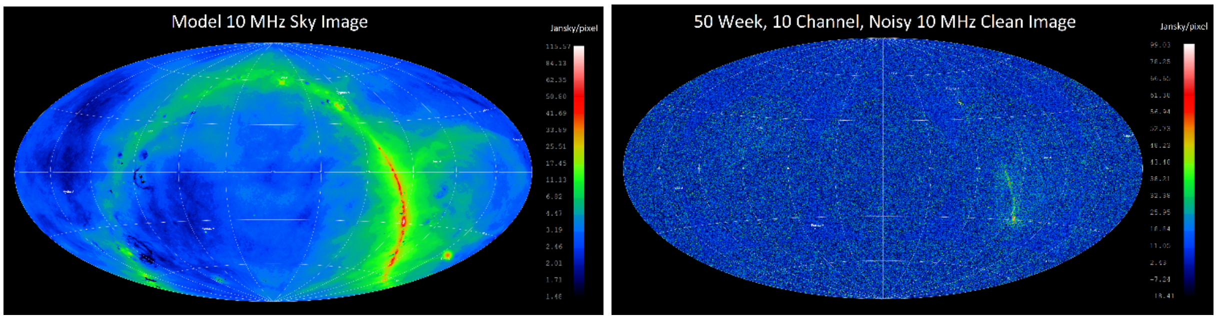

Figure 6*: The left panel shows a sky model at 10 MHz, made using estimates of free-free absorption, while the right panel shows a simulated SunRISE map at 10 MHz, using 50 weeks of integration. Adding short baselines from a lunar array will dramatically improve the sensitivity to large-scale Galactic features.*

One scientific analysis tool under development is software to create all-sky maps from space-based radio interferometer data. This software will be applied to future SunRISE data to yield a cutting-edge map of the low frequency sky, which in turn will be used in conjunction with the LuSEE CLPS mission for foreground determination.

Initial simulations have now been completed, with a basic sky map made with predicted SunRISE orbits at a single set of frequencies near 10 MHz (Fig. 6). This figure shows a sky model when using estimations of the effects of free-free absorption below 10 MHz, as well as the expected SunRISE map after 50 weeks of integration, where the sensitivity compared to the base sky map is apparent via the relative lack of contaminating features. Further progress is needed to make this all-sky mapping software ready for real data, including incorporation of the antenna beam patterns, filtering of transient bursts for quiet data selection, and extending the routine to be usable across the entire low frequency band. The SunRISE-recovered sky map will use 50 weeks of integration, relying on the orbital drift over time to fill out the synthetic aperture to acquire a higher quality image. The recovered sky map will have good detections of all the bright sources as well as the core of the Galactic plane.

1.3 Low-Frequency Sky Modelling for Upcoming CLPS Radio Science Observations

The FIELDS radio instrument on the Parker Solar Probe (PSP) provides new data on the low frequency sky to support the lunar-landed payloads ROLSES and LuSEE. Although the instruments on board PSP were designed for solar experiments, spectra from the FIELDS instrument can also be used to study emission from the galaxy below 10 MHz. This is of particular interest because Earth's ionosphere prevents measurement of the sky at these frequencies, making precise characterization of the anisotropic galactic emission difficult. Previous measurements are not sufficiently detailed to understand the foreground for upcoming 21-cm cosmology lunar-based observations. The FIELDS instrument is composed of four monopole antennas, very similar to those that will be used for ROLSES and LuSEE. While the beams of the antennas are large, PSP undergoes rotation maneuvers near aphelion in which the antenna beams sweep across the sky (and thus the galaxy), producing a periodic modulation in the power received by the instrument.

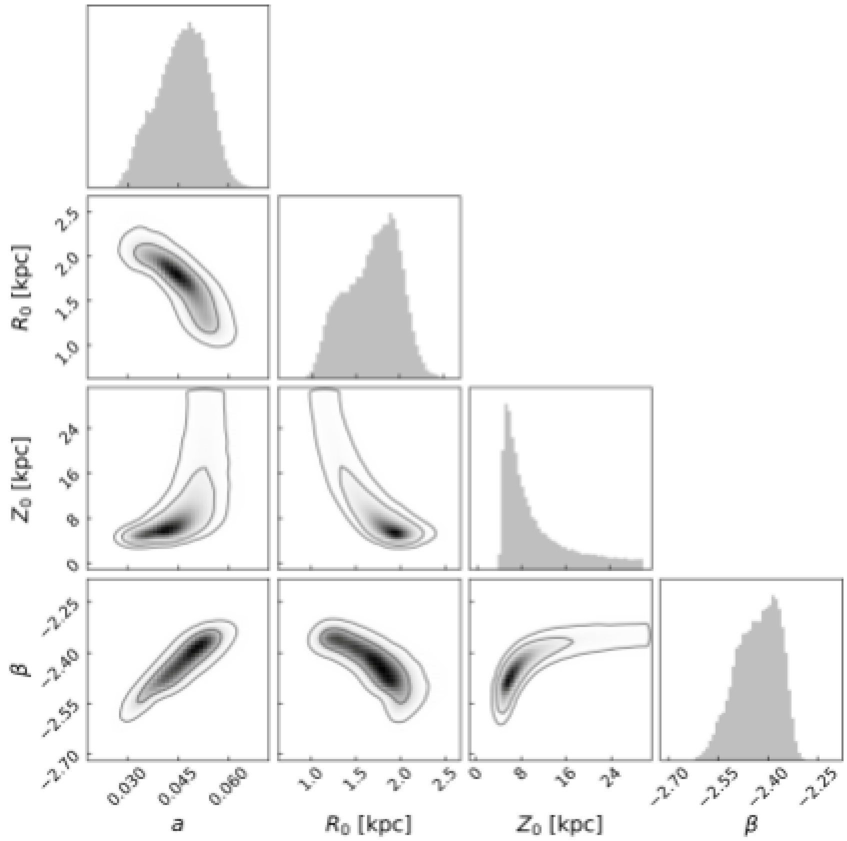

Figure 7: *Triangle plot of parameter constraints generated by fitting a forward model of observations to the FIELDS data (from Bassett et al., submitted to ApJ). The first parameter (a) is related to the free-free absorption model, while the remaining three parameters are from the galactic emissivity model.*

Figure 6 shows the posterior constraints on a 4-parameter model of the sky, obtained by using a Nested Sampling algorithm to fit spectra from 5 different days over 2 years in which PSP performed a rotation maneuver. The components of the model are the antenna beam, the Galactic emissivity, and absorption from free electrons. A numerical simulation of the antenna beam was performed with CST Microwave studio, a widely used software suite installed on a supercomputer at Colorado. We use an analytic expression for the emissivity (synchrotron radiation) that assumes a cylindrically symmetric distribution for the Galactic emission and falls off exponentially in the radial and z directions. We employ a model for free-free absorption that uses pulsar data to estimate the free electron density and to calculate the optical depth. Reconstructions of the FIELDS spectra with this model yield very good agreement, accurately producing a maximum near ~3 MHz caused by free-free absorption. These initial constraints on the low frequency sky from FIELDS can be thought of as a precursor to the upcoming lunar observations with ROLSES and LuSEE. This work was a collaboration between CU-Boulder and UC-Berkeley members of NESS led by CU graduate student Neil Bassett (Bassett et al., accepted for publication in ApJ, https://arxiv.org/abs/2301.09612).

1.4 Exploration Research: Surface Telerobotics and Lunar Surface Electronics

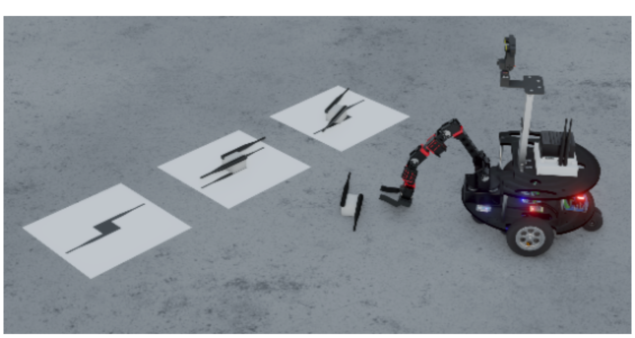

Figure 8: *Shown above is the digital twin of our Armstrong rover, developed for novel problem-solving techniques for e.g., instances of misalignment of dipole antenna polarization axes. Such rovers will be used for re-alignment strategies in our VR/AR "sandbox" and then applied to the physical rover environment.*

Deployment of a lunar low frequency interferometric array will require a long-duration robotic mission involving many autonomous actions. However, if a failure occurs, human intervention will be needed to identify, isolate, and recover in an efficient manner. Current troubleshooting methods for rovers include the use of physical models (e.g., the Perseverance engineering unit) and analog terrain (e.g., the "Mars Yard" at JPL). While this approach has proven effective for many situations, drawbacks include restricted portability, difficulty in simulating gravity, and no method of creating many replicas of the equipment and rovers themselves.

We are designing novel methods for rover problem-solving and error recovery that leverage new technologies to enable stereoscopic video pass-through and 3D environment reconstruction. Through stereoscopic cameras mounted on a rover, operators can gain the ability to see depth from the rover perspective and/or interact with a 3D model of the environment. Using virtual reality (VR) headsets coupled with methods in 3D point-cloud generation and environment reconstruction allows teleoperators to "virtually walk around" in a simulated version of the robot environment.

Operators interact with a rover digital twin that uses the same control interface, kinematics, and hardware model to explore a high-fidelity reconstruction of the local environment. Solutions developed in VR are then made operational by teleoperating the physical rover. An overview of our experiment to test methodologies for robotic problem solving was presented at a conference and published this year in a paper led by undergraduate team members (Curlin et al. 2022).

NESS Team member and UNC Ph.D. student Michael Walker, under the supervision of NESS Co-I Safir and Burns, developed a Cyber-Physical Control Room Robot Teleoperation and Supervision Interface Design that provides both exocentric and egocentric perspectives during exploration. The Control Room is a novel virtual shared workspace for multi-user real-time collaboration using VR/AR technologies. This research provides further justification for the inclusion of mixed reality hardware and the required communication infrastructure in future lunar surface missions; we believe that with more feature-rich interfaces such as these, scientists will be better equipped to leverage the full capabilities of their robots and learn more about both the lunar environment and the early universe without the need of a physical human presence.

Figure 9: *This prototype innovatively unifies concepts from both cyber-physical and virtual control room paradigms that are needed to deploy radio telescopes and explore the Moon. It provides users with egocentric (live stereoscopic video stream) and exocentric (3D environmental reconstruction) information to enhance detail and overall situational awareness.*

2. Inter-team/International Collaborations

Burns continued to collaborate on a ESA-funded concept study called the Astrophysical Lunar Observatory (ALO). This is a low frequency radio array from the lunar farside with elements in common to the NESS FARSIDE concept. The NESS Team has formed a strong partnership with a European group funded by ESA to explore designs for low frequency radio arrays on the Moon. Professor Marc Klein Wolt from Radboud University in the Netherlands leads an ESA Topical Team developing the concept for ALO. The science goals for ALO are like FARSIDE with a focus on measuring the global 21-cm spectrum from the early star-forming epochs of the Universe. The proposed ALO would synergize with the ESA/US human lunar exploration program while building on European technology heritage. Burns and Klein Wolt presented the FARSIDE and ALO concepts and discussed a potential NASA/ESA collaborative framework at two conferences in 2022 - the NESC "Unique Science from the Moon in the Artemis Era" workshop held at KSC in June, and the NASA Exploration Science Forum in Boulder, CO in July. We also proposed to SSERVI Director Schmidt the establishment of a SSERVI working group on "International Design Studies of Lunar Radio Arrays."

3. Public Engagement

NESS and the Fiske Planetarium at the University of Colorado, in collaboration with TEND Studio, SSERVI, and Lockheed Martin, premiered a feature length, full dome film titled *Forward! To the Moon* at CU-Boulder in February, 2022. SSERVI Director Schmidt, NASA ESSIO Deputy AA Joel Kearns, and Lockheed Martin VP Lisa Callahan joined a panel discussion following the showing of the film. This production featured the NASA Artemis and Commercial Lunar Payload Services (CLPS) Programs, along with the development of surface telerobotic deployment and construction that will be critically important to exploration and science investigations of the Moon and for advancing on to Mars. *Forward! To the Moon* had additional premiers at (1) the Chabot Science Center Planetarium in Oakland, CA, in collaboration with NASA Ames management in late February, (2) the Houston Museum of Natural Science planetarium in collaboration with NASA JSC management in March, and (3) the Intuitive Planetarium at the U.S. Space and Rocket Center in collaboration with NASA MSFC management in May. *Forward! To the Moon* has been distributed free of charge to over 300 science museums in the U.S. and abroad, resulting in over 0.5 million views so far.

In the summer of 2022, NESS member Nivedita Mahesh mentored a high school student from Saguaro High School. As part of the high school's Math and Science Academy, the student (who was a junior then) worked with N. Mahesh for six weeks on a STEM project. The project chosen was related to FARSIDE, and the student developed a python code to assess how many unknown planets would be detected by FARSIDE, given the demographic data from Kepler.

Figure 10: *Panel discussion at Chabot Planetarium (Oakland) featuring NASA ARC Director Eugene Tu, Dan Andrews, Kari Byrum, and Jack Burns.*

4. Equity, Diversity, Inclusion and Accessibility (EDIA)

1. As part of our outreach project to develop the feature length planetarium program *Forward! To the Moon*, diversity was foremost in our planning. The film will be seen by tens of thousands in planetariums world-wide, showing a new generation of astronauts, including many women and persons of color as part of the 21st century Artemis class of astronauts. We included interviews from a diverse group of young students who are excited by space and travel to the Moon and Mars to show that space careers are open to everyone.

5. Student/Early Career Participation

Undergraduate Students

1. Anna Tsai (UCLA): theoretical 21-cm studies
2. Natsuko Yamaguchi (UCLA): theoretical 21-cm studies
3. Roy Zhao (UCLA): theoretical 21-cm studies
4. Phaedra Curlin (University of Colorado Boulder): surface telerobotics
5. Madaline Muniz (CU-Boulder): surface telerobotics
6. Alexis Muniz (CU-Boulder): surface telerobotics

Graduate Students

7. Adam Trapp (UCLA): theoretical 21-cm studies
8. David Bordenave (Department of Astronomy, University of Virginia): experimental 21-cm studies
9. Neil Bassett (University of Colorado Boulder): 21-cm data analysis studies
10. Joshua Hibbard (University of Colorado Boulder): 21-cm data analysis studies
11. Michael Walker (University of Colorado Boulder): surface telerobotics
12. Nivedita Mahesh (Arizona State University) (Jan-Aug): experimental 21-cm studies
13. Johnny Dorigo Jones (University of Colorado Boulder): 21-cm data analysis studies

14. Sahil Hedge (UCLA): theoretical 21-cm studies

Postdoctoral Fellows

15. Alexander Hegedus (University of Michigan): simulating space-based radio arrays
16. Marin Anderson (California Institute of Technology, Jet Propulsion Laboratory): extrasolar space weather
17. Steve Murray (Arizona State University): 21-cm data analysis studies
18. Jordan Mirocha (McGill University/JPL): theoretical 21-cm studies
19. Bang Nhan (National Radio Astronomy Observatory): experimental 21-cm studies
20. Nivedita Mahesh (Caltech) (Oct-Dec): experimental 21-cm studies

6. Mission Involvement

1. **ROLSES:** The Radiowave Observations at the Lunar Surface of the Electron Sheath (ROLSES) experiment will launch in mid-2023 on the Intuitive Machines IM-1 NOVA-C lander. ROLSES will be the first radio-frequency instrument to investigate the plasma environment in the lunar polar region and to measure the fidelity of radio spectra on the surface, providing spectra from 5 kHz – 30 MHz which is not accessible from Earth. ROLSES was among the first payload selections for the CLPS program, but very little funding was allocated for science modeling. Burns is a ROLSES science Co-I. NESS team members Burns, Rapetti, and Bassett have been performing simulations and analysis work to prepare for the upcoming observations from ROLSES. The analysis of the PSP/FIELDS data described in section 1.4 is a precursor for the analysis of ROLSES data.

2. **LuSEE:** The Lunar Surface Electromagnetics Experiment (LuSEE) is composed of two separate instruments, LuSEE-Light and LuSEE-Night. NESS Team members are extensively involved in the development of the science and modeling for LuSEE-Night, which is jointly funded between the US Department of Energy (DOE) and NASA. LuSEE-Night will perform low frequency observations from the radio-quiet lunar farside, a longtime goal of NESS, investigating the feasibility of measuring the global 21-cm cosmological signal from the lunar environment. NESS team member N. Bassett produced simulations of the apparent horizon from several potential landing sites for LuSEE-Night (using the code and algorithm outlined in Bassett et al. 2021). These horizon simulations were used to select the landing site that exhibited the lowest horizon, blocking the least amount of sky.

3. **FARSIDE:** The Dark Ages of the early Universe was singled out by the Astro2020 Decadal Survey as THE discovery area in cosmology for the next decade. The Dark Ages, along with detecting radio emission from nearby exoplanets, are the primary science goals for this array of 256 dipole antennas. FARSIDE was identified by Astro2020 as one possible Probe-class mission. See further mission details above. Burns is the PI and Hallinan is Deputy PI of the FARSIDE concept. Updates on the development of FARSIDE were reported earlier in the report.

4. **SunRISE:** In the past year the Sun Radio Interferometer Experiment (SunRISE) mission passed its Systems Integration Review, a major milestone that led the mission into Phase D of operations, where systems assembly, integration, and testing activities take place. Co-I Kasper and Collaborator Hegedus presented the mission overview and the implementation of the science data system respectively. The SunRISE mission has an estimated launch date of mid-2024, and a primary mission length of 12 months. The mission is currently preparing for the Interferometer Level Performance Test, where the entire team will undergo a realistic, multi-day test. In this test, the spacecraft will be laid out in a special trailer at JPL and record synthetic radio and GNSS observations, and then realistic data processing will be done at JPL and University of Michigan.

5. VIPER: During this past year, NESS Co-I Fong served as the deputy rover lead for the Volatiles Investigating Polar Exploration Rover (VIPER) mission. To support NESS research and outreach activities, Fong actively worked to disseminate VIPER developed data, including the VIPER Environmental Specification and synthetic digital elevation model generation software. Fong also served on the Independent Assessment Team for "Lunar Vertex" (Payloads and Research Investigations on the Surface of the Moon program, PRISM) and the "Moon Ranger" lunar rover mission (Lunar Surface and Instrumentation and Technology Payload program, LSITP), providing robotics expertise to major gate reviews.

7. Awards (as applicable)

1. COSPAR Outstanding Paper Award for Young Scientists, Neil Bassett, Graduate Student.
2. Colorado Department of Astrophysical & Planetary Sciences Carl Hansen Memorial Fellowship, Neil Bassett, Graduate Student.