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 that investigates the design and deployment of low frequency radio telescopes on the lunar surface. The purposes of these radio telescopes are 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; radio emission from the Sun; and extrasolar space weather and 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 shielded by the Moon on its farside. 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 2022 (near side) and in 2025 (far side). For outreach, NESS published a new website to explain the Cosmic Dawn and Dark Ages to a general audience and recently completed a SSERVI-funded full-dome, feature-length planetarium film entitled *Forward! To the Moon.*

1. Team Project Report

1.1. Primordial Hydrogen Cosmology

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. Theoretical Predictions of the 21-cm Signal

We describe our progress in designing such telescopes below, but central to the effort is improving our understanding of how the spin-flip signal can be harnessed optimally in order to learn about these processes, which requires theoretical modeling of the expected signals. Co-I Furlanetto worked to improve predictions of galaxy populations during this era, which are essential to predicting the spin-flip background. In Furlanetto & Mirocha (2021), bursty star formation in small galaxies was explored along with the effects of the buildup of stellar mass during the Cosmic Dawn. It was demonstrated that such bursts can have substantial effects on the earliest phases of galaxy formation, which will be a prime discovery area for lunar radio telescopes. Furlanetto is continuing to improve these models with two UCLA undergraduate students. Anna Tsai is exploring how globular cluster formation during this bursty phase may affect galaxy formation, while Natsuko Yamaguchi is studying how chemical enrichment with heavy elements occurs in this era (which has strong implications for the transition from exotic "first stars" to normal galaxy formation).

One of the challenges of such modeling efforts is ensuring that theoretical predictions are not based too strongly on our expectations, given the many uncertainties in this early era. Mirocha et al. (2022) have developed a

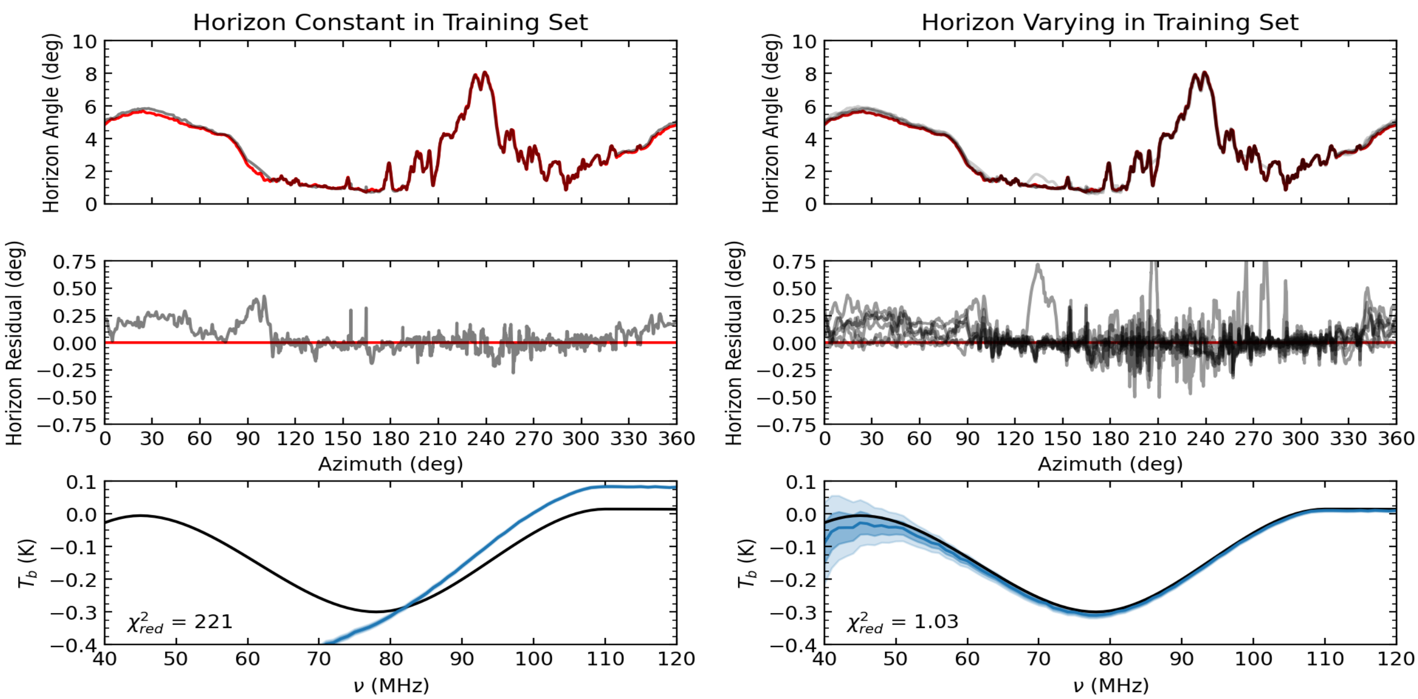

Fig. 1 - Top: Horizon profiles from the Schrodinger Basin on the lunar surface used for the simulated data realization (red) and the foreground training set curves (grey). Middle: Residuals between the horizon profiles used to create the foreground training set (grey) and the fiducial horizon used to create the data realization (red). Bottom: Simulated extracted 21-cm signal compared to the input (black). When our training set formalism is not used for modeling the horizon, the signal extraction is poor (left). When a horizon training set is fully incorporated in the analysis, the signal extraction is precise and unbiased (right).

phenomenological approach to modeling the spin-flip background that bypasses many of the assumptions of galaxy-based prescriptions. In this paper, the framework was applied to the reionization era, but it will also be applied to the era of the first stars and black holes that will be studied with lunar radio telescopes. Additionally, in Trapp & Furlanetto (2022) it was demonstrated that next generation galaxy surveys can measure the large-scale environments of survey fields, which will improve cross-correlations with the spin-flip background and enable new physical probes.

1.1.2. Experimental Progress

Experimental teams seeking to detect the 21-cm signal have gained considerable experience with pathfinder instruments over the last decade. It has become apparent that instrumental and calibration effects need to be included directly in science data analysis. This can be done by modeling the instrumental and calibration effects, and simultaneously fitting models to the observations that include both astrophysical components and calibration components. Bayesian analysis provides a robust framework for implementing this integrated strategy. Collaborator Steven Murray, working with Co-I Bowman, has been implementing a fundamental overhaul of the analysis of EDGES global 21-cm observations, developing an open-source calibration and analysis software pipeline that is focused on enabling Bayesian inference. Bayesian forward modeling allows for the rigorous propagation of instrumental uncertainties through the entire analysis chain, and facilitates comparison of models and datasets in a statistically rigorous way. This is of increasing importance as multiple experiments are now yielding results that must be evaluated in tandem. This work has motivated new laboratory tests to better identify errors and uncertainties in calibration measurements for EDGES.

1.1.3. Data Analysis Pipeline for Global 21-cm Signal Experiments

The fourth and final paper (Tauscher et al. 2021) in the series describing the framework of the NESS 21-cm global signal data analysis pipeline was published in the *Astrophysical Journal*. Paper IV describes how instrumental effects introduced by electronic receivers can be rigorously accounted for using a technique termed analytical marginalization of linear parameters (AMLP). This paper and the corresponding additions to the pipeline software are crucial for extracting the global 21-cm signal from data produced by real instruments.

In another paper (Bassett et al. 2021), the effect of the shape of the landscape horizon on low frequency global signal observations was examined. Published in the *Astrophysical Journal*, the paper shows how incorrect assumptions on the shape of the (Earth or lunar) horizon can produce significant biases in the extracted signal, particularly when analyzing multiple correlated spectra, which we have shown previously to produce the most precise constraints on the global signal (Tauscher et al. 2021a). Fig. 1 shows the importance of fully modeling the horizon using our training set framework for simulated observations from the Schrodinger Basin on the lunar farside. In conjunction with the paper, an open source Python package, `SHAPES`, which is able to calculate the apparent horizon for any location on the lunar surface using LRO LOLA elevation data, was publicly released.

1.1.4. Instrument Development

1.1.4.1. Antenna and Advanced Receiver Development

Work over the past year, led by Co-I Bradley and his team, has focused on four areas of instrument development: patch antenna, receiver front-end with calibration, pilot tone circuitry, and various antenna simulations. The patch antenna consists of a stacked structure containing a dielectric material having a relative dielectric constant of 4.5. A solid polymer with this value would be too massive, so a composite approach was adopted. Three 1:15 scale versions were fabricated and evaluated, the last containing 130 small pieces of high dielectric constant ceramic material embedded into a foam substrate. The mass of the full-size antenna would be reduced to about 10 kg. A report on the ceramic evaluation was written. A receiver front-end board consisting of three amplifiers, one filter stage, and FET switches was also developed and evaluated together with a calibration board containing thermal noise sources. A prototype pilot tone injection system consisting of a direct digital synthesizer, power detector, and controller was

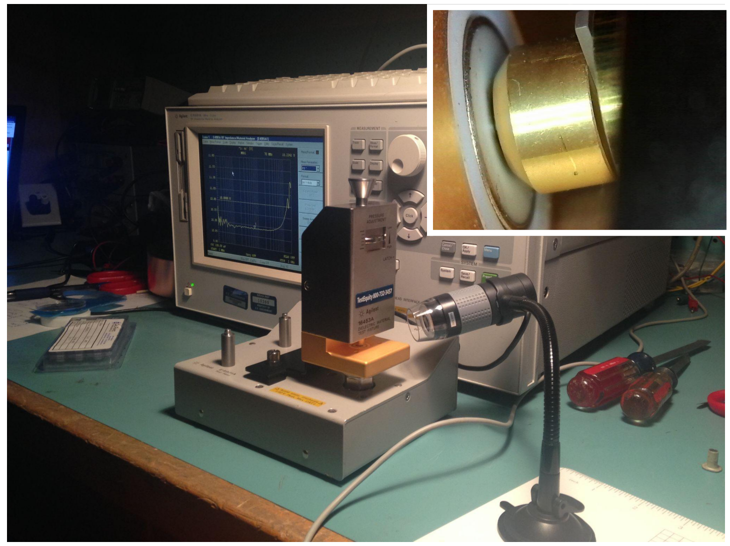

Fig. 2 - Test setup for measuring the dielectric constant and loss tangent of the ceramic material used in the patch antenna. Inset shows a sample of the material mounted on the fixture.

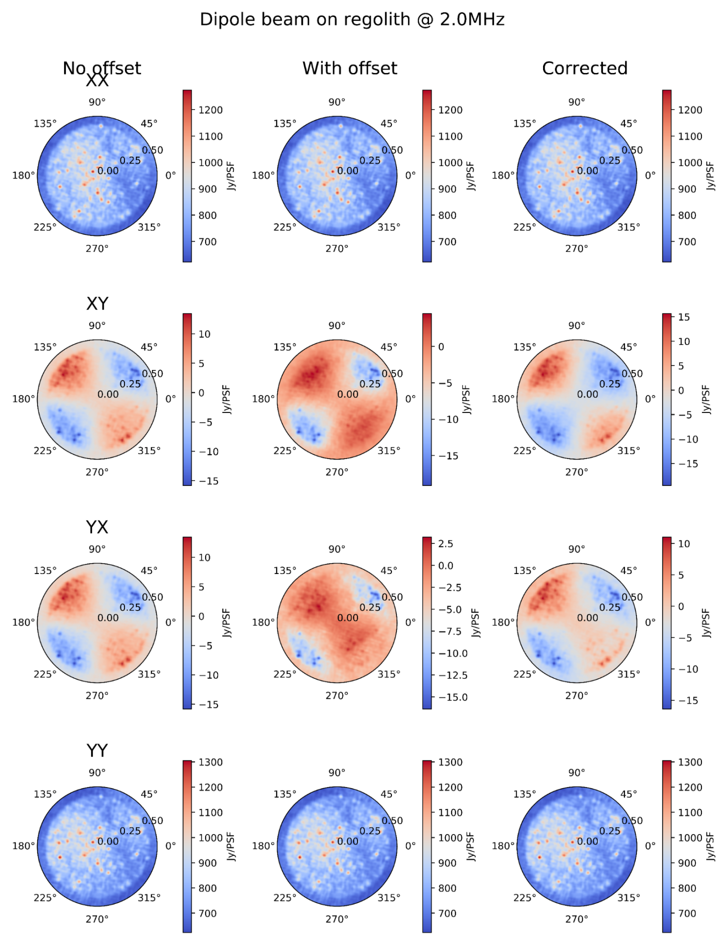

Fig. 3 - Images of the GLEAM radio sources captured by the XX, YY, XY and YX dipole correlations of the FARSIDE array. The images are produced by the custom interferometric simulation pipeline. Three cases are shown: (left) no offset between the orthogonal dipoles in the array, (middle) 50m offset between the dipoles and (right) correction applied to the images of the offset case. The offset case changes the image produced by the XY and YX correlation and the correction applied restores the image to the original case.

developed and the circuit board layout completed. Electromagnetic study for the high-band composite dielectric patch antenna design as well as the low-band stacer antenna with the lunar lander were performed using commercial 3D electromagnetic simulation software, CST Microwave Studio. The error budget for the science result was estimated by constraining the variations on the antenna radiation pattern due to lunar environmental effects, such as, relative errors in the simulated antenna radiation patterns at different combinations of lunar regolith properties (in terms of dielectric permittivity and loss tangent values).

1.1.4.2. FARSIDE Concept Instrumentation

Mahesh, Bowman et al. 2022 (in prep.) performed a detailed study of the expected polarization imaging performance of the FARSIDE array on the lunar surface. A custom interferometric simulation pipeline was developed that incorporates the beam patterns of the dipoles on the regolith and the *uv*-coverage of the array (projected baselines on the sky). The pipeline was used to estimate and quantify the effect on the polarization performance of FARSIDE's novel dipole arrangement, which has non-collocated phase centers of the orthogonal dipoles. For this study, a mock sky created using the GLEAM catalog of low-frequency radio sources was used. A correction to be applied on the image products was formulated to adjust the results for offset errors.

In Hegedus, Burns, Hallinan et al. 2022 (in prep) a simulated FARSIDE array was laid out and used to observe the redshifted 21-cm signal from the frequency range 10-80 MHz. The output of a 300 Mpc 21cmFAST run was used as ground truth and translated to a small field of view imaging simulation. Astropy was used to estimate the angular sizes of 300 Mpc structures at a given redshift. Two versions of the ground truth were made: a version using a vanilla 21cmFAST cosmological model to generate the 21-cm signal, and a toy exotic physics version where a 0.1 k/Mpc wave was injected into the data to simulate the presence of fractionally ionized dark matter in the early universe. A custom CASA pipeline was used to simulate the visibility response of the 256 element FARSIDE array, then the widefield imaging software WSCLEAN was used to image and deconvolve the data in total intensity (Stokes I). The recovered FARSIDE images were then analyzed as a function of spatial spectral power, revealing that FARSIDE can successfully discern between the two models. An example of this analysis for simulated FARSIDE observations at 40 MHz is shown in Figure 4. This will lead into future work where simulated recovered FARSIDE observations will be put through the NESS 21-cm

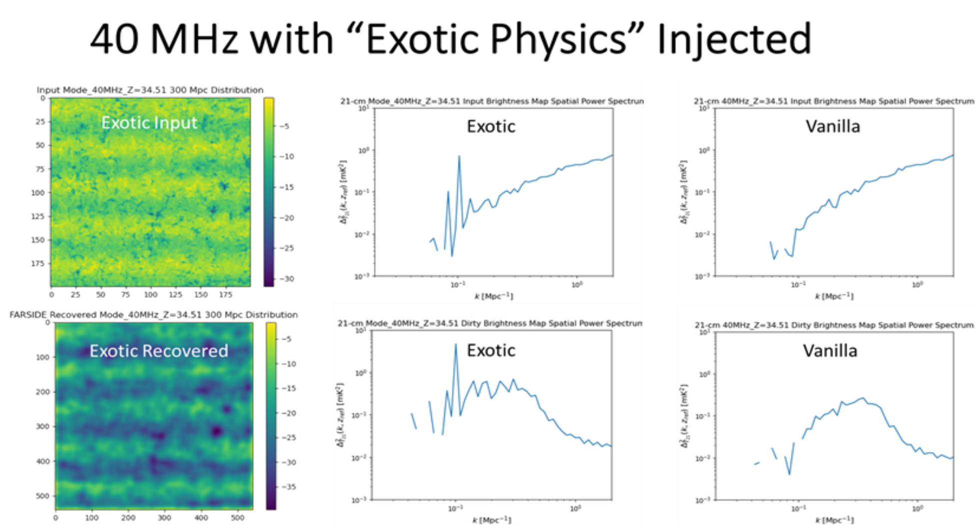

Fig. 4 - Top left: Exotic ground truth of the redshifted 21-cm signal at 40 MHz made from an altered 21cmFAST run. Top middle: Spatial power spectrum of top left, spike at 0.1 k/MPc showcasing the added "exotic physics" from fractionally ionized dark matter. Top right: Spatial power spectrum of vanilla output of 21cmFAST with no exotic physics injected. Bottom left: FARSIDE recovered image of exotic physics scenario. Bottom middle: Spatial power spectrum of bottom left, with visible spike still at 0.1 k/MPc. Bottom right: Spatial power spectrum of recovered FARSIDE image of the vanilla physics scenario, lacking the 0.1 k/MPc spike.

pipeline. The **pylinex** code will allow us to recover the exact set of cosmological parameters behind the recovered 21-cm signal, which will be separated from a realistic galactic background.

1.1.4.3. Development of CLPS Missions: ROLSES and LuSEE Instrumentation

In anticipation of upcoming NASA-funded CLPS missions, Radio wave Observations at the Lunar Surface of the photoElectron Sheath (ROLSES, scheduled to land in mid-2022) and Lunar Surface Electromagnetics Experiment (LuSEE, scheduled for the farside in 2025), NESS team members conducted detailed modeling of the effects on the antenna beam from the electromagnetic properties of the lunar subsurface. Numerical modeling of antenna beams was conducted with CST Microwave Studio (see above). Electrical properties of the lunar subsurface were varied within reasonable bounds such that the beams could be compared over a range of parameter space. The beam simulations were then fed through the analysis pipeline described in Sec. 1.1.3 in order to study how the lunar soil properties might influence recovery of the 21-cm global signal from lunar observations. One key finding of this analysis was that the relative permittivity of the soil was far more influential than the dielectric loss in terms of its influence on the antenna beam. Ongoing work in this area incorporates more complicated soil models including inhomogeneous subsurface structure.

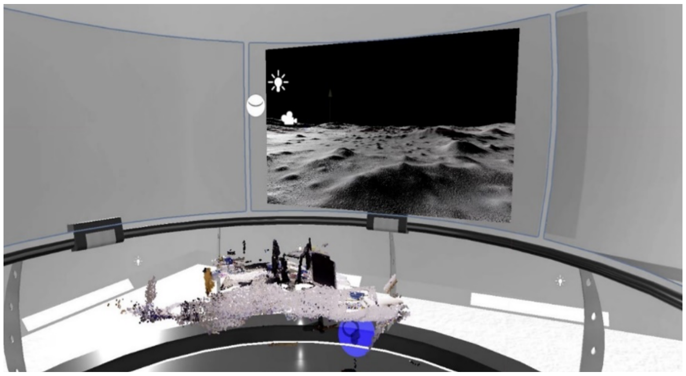

Fig. 5 - The NESS hybrid augmented virtuality interface design unifies concepts from both cyber-physical and virtual control room interfaces by providing mobile space robot operators with egocentric (live 3D video stream) and exocentric (3D dense point cloud environmental constructions) perspectives to enhance telepresence and situational awareness.

Burns, MacDowall, Bale, Hallinan, Bassett, Hegedus published a paper in a special lunar-oriented issue of the *Planetary Science Journal* on "Low Radio Frequency Observations from the Moon Enabled by NASA Landed Payload Missions" which described the ROLSES and LuSEE radio astronomy instruments along with FARSIDE.

1.2. Lunar Exploration and Surface Telerobotics

NESS contributions to lunar exploration efforts involve research on teleoperation of rovers on the lunar surface for deployment and construction of low frequency radio telescope arrays. The NESS team continued to research new methods to support low-latency, interactive telerobotics for future lunar missions. To examine the capabilities that augmented, virtual and mixed-reality interfaces offer for improving telerobotic performance, the team studied the effectiveness of providing both 1st person (egocentric) virtual control rooms and 3rd person (exocentric) cyber-physical configurations. To examine the benefits of high-fidelity simulation for robotic operations, the team implemented a "virtual recovery sandbox," which is a recreated, manipulable virtual space representation of a robot's state and its operational environment.

To study the capabilities that virtual and mixed reality (VAM) technologies can provide for lunar surface robotics, NESS team members are exploring multi-perspective augmented virtuality head-mounted display (HMD) interface designs. This research is led by graduate student Michael Walker, supervised by Professors Dan Szafir and Jack Burns. To mitigate the nauseating effects of directly streaming stereo video feeds to HMD Interfaces, two augmented virtuality HMD Teleoperation Interface paradigms have arisen from state-of-the-art research in the VAM Human-Robot Interaction field: Virtual Control Room (robot egocentric) and Cyber-Physical Interfaces (robot exocentric). In both interface styles, the user's point-of-view is decoupled from the robot's point-of-view to remove the proprioception system conflicting cues. By placing the user in an augmented virtuality environment, the user's eyes are represented by virtual cameras in the virtual space that move freely with the user's head and body movements. This decoupling method helps mitigate nausea caused by communications/hardware delays and/or imperfect mappings between user head motion and robot head motion. In this research, we looked to combine both the egocentric (1st person) and exocentric (3rd person) designs to examine the overall effectiveness and optimal use cases for our hybrid design paradigm. The hypothesis is that our combined style of interface will offer significant operational advantages for remote navigation and manipulation teleoperation and supervision tasks if a robot operator can simultaneously use or switch at-will between both egocentric and exocentric perspectives. Additionally, our hybrid Cyber-Physical Virtual Control Room (Figure 5) can facilitate multi-user collaboration for joint robot teleoperation, supervision, and data analysis via real-time virtual avatar streaming.

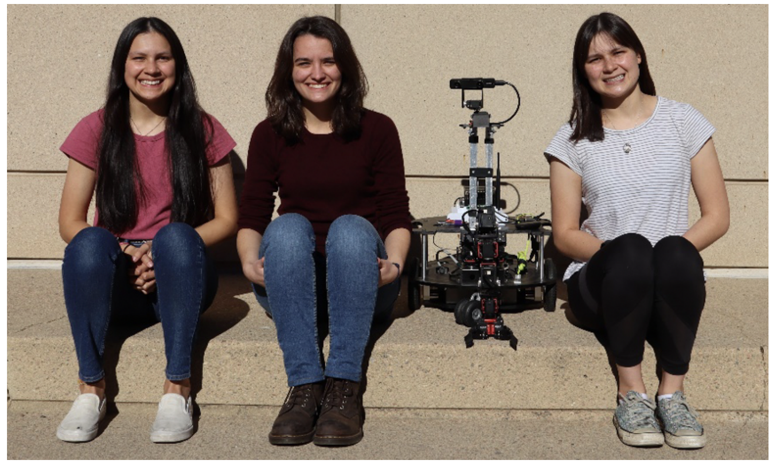

Fig. 6 - Undergraduate members of the NESS Telerobotics Lab team along with the *Armstrong* rover. From left to right: Madaline Muniz, Phaedra Curlin, and Alexis Muniz.

NASA is planning to create a sustainable presence on the Moon during this decade. This includes the construction of the Lunar Gateway which will allow for low-latency communications on the Moon's surface. This would be useful in missions like FARSIDE, which will require rovers to deploy a radio array on the farside of the Moon. If an autonomous assembly failure occurs, operators will need to teleoperatively recover from the failure. To aid with the troubleshooting process, members of the NESS Telerobotics Laboratory at the University of Colorado Boulder (Figure 6) have created a virtual reality (VR) platform that includes a digital twin of our rover in a simulation of its environment that currently functions with the lab's physical rover + mechanical arm called *Armstrong* (Figures 6, 7). The VR twin is CAD-accurate and uses the same control interface as the physical one. The virtual rover also takes advantage of novel technologies on *Armstrong* like its stereoscopic camera that lets the teleoperator see from the rover's perspective and move the camera with head movements. The simulated environment can use point-clouds generated from this camera or use real-world

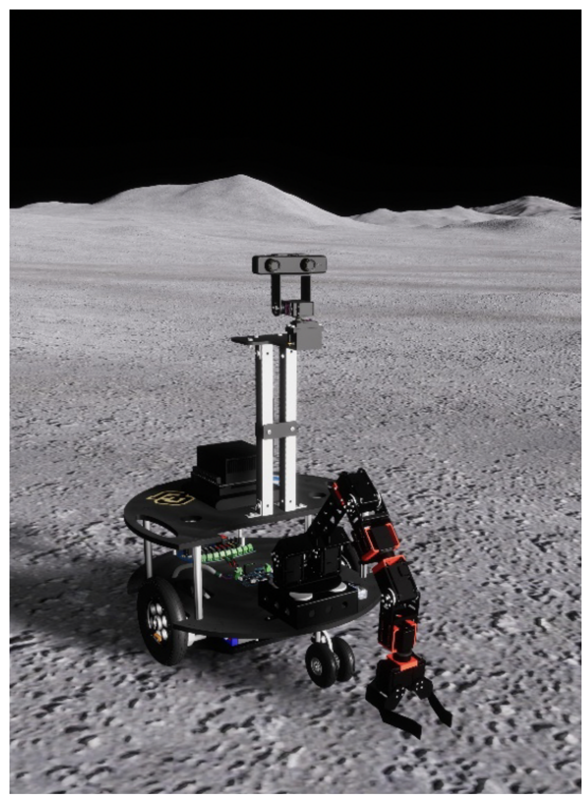

Fig. 7 - The digital twin of the NESS *Armstrong* rover + mechanical arm on the simulated lunarscape within NESS's VR construct.

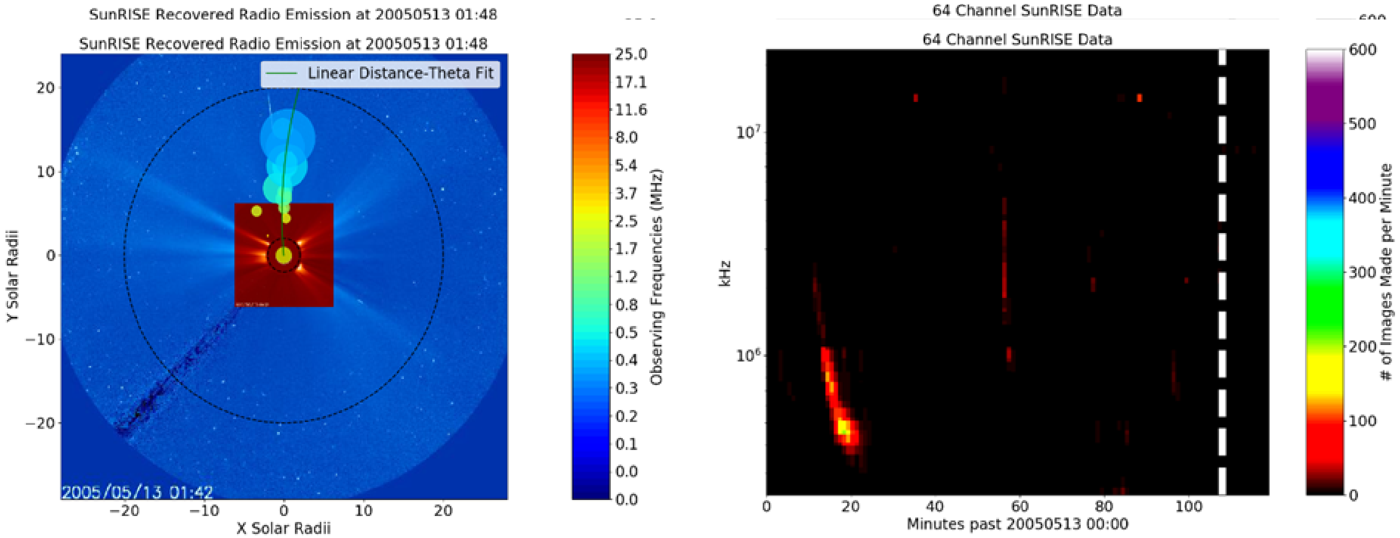

Fig. 8 - Left: SunRISE summary plot showing localizations of radio emission over LASCO C2 & C3 coronagraphs. Right: The number of images made across frequency and time, indicating the fit signal above background levels, with the type III burst showing up between 15-20 minutes into the simulated data.

measurements and imaging. The VR platform is similar to physical duplicates traditionally used on Earth for troubleshooting rovers but is risk-free, resettable, and portable. A baseline experiment is under development to evaluate the effectiveness of the VR platform for troubleshooting. A successor experiment will compare the VR platform to the use of a physical twin for recovery from deployment failures.

1.3. Heliophysics

Work on the Heliophysics mission Sun Radio Interferometer Space Experiment is progressing nicely, with Co-I Kasper and Collaborator Hegedus pushing forward on the operational design and science analysis pipeline for the mission. An alpha version of the SunRISE Science Data System pipeline is now complete, with simulated data going from uncalibrated spectra, to calibrated spectra, to cross correlated visibilities, to images and gaussian fits on the sky. Simulated SunRISE radio data was made by translating Wind/WAVES data into SunRISE sensitivities, with the location of any fit signal over the background originating from the 12 o'clock angle. An example of these final gaussian fits for a type III radio burst is shown in Figure 7. On the left are the fit emission location and sizes for the 2 hours of data including a type III burst, plotted over LASCO C2 & C3 coronagraph data. The recovered emission lies along the 12 o'clock angle, matching the input location for each frequency. The right panel shows the number of images made across frequency and time, indicating the fit signal above background levels, with the type III burst showing up between 15-20 minutes into the simulated data.

The development of the SunRISE science processing pipeline will continue to mature over the next 2 years as SunRISE works towards launch in mid-2024. In particular, all the ground-based calibration data that will be generated over the coming years will be integrated into the science pipeline.

1.4. Extrasolar Space Weather

The detection of exoplanetary radio emission, as well as the detection of stellar radio bursts indicative of coronal mass ejections (CMEs) and stellar energetic particle events (SEPs), is critical for diagnosing planetary habitability and understanding the role that planetary magnetospheres play in shielding their atmospheres from the space weather environments of their host stars. Current ground-based low-frequency arrays are paving the way for future lunar-based low-frequency radio telescopes, such as FARSIDE, which will be vital for expanding our reach to the terrestrial-like magnetospheres that can only be detected from space.

The Owens Valley Radio Observatory Long Wavelength Array (OVRO-LWA, led by NESS Co-I Hallinan) is one such ground-based array serving as a pathfinder for future lunar-based arrays like FARSIDE, providing a framework for the operation and design of a survey targeting extrasolar space weather science from the lunar surface. OVRO-LWA targets nearby stellar systems to monitor for stellar CMEs and SEPs, as well as radio signatures of planetary magnetospheres – specifically, the Jovian-like magnetospheres that are detectable from within Earth's ionosphere. The OVRO-LWA is a 352-element dipole array in California, operating at sub-100 MHz frequencies and imaging the entire viewable hemisphere at 10-second cadence. This allows for the simultaneous monitoring of thousands of stellar sources for radio emission indicative of space weather events.

In the last year, significant progress has been made in the ongoing upgrade of the OVRO-LWA, which, when completed, will expand the array from its previous 288-element configuration to the final 352-element configuration spanning a 2.6 km diameter area. The upgrade also features a full redesign of the analog and digital signal processing systems, as well as efforts to measure and characterize all 352 antenna beams via multiple methods (including via drone). Precise knowledge of the dipole beam patterns will be essential for achieving the sensitivity necessary for detecting stellar and planetary radio emission. Demonstrating this capability with a ground-based array like OVRO-LWA will impact strategies employed by lunar-based arrays like FARSIDE.

2. Inter-team/International Collaborations

Burns continued to collaborate on an ESA-funded concept study proposal called LunarLOFAR. This is a low frequency radio array from the lunar farside with elements in common to the NESS FARSIDE concept. We are planning to do a joint workshop in 2022 on science with lunar farside low radio frequency arrays.

3. Public Engagement

3.1. From Cosmic Dark to Cosmic Dawn: An Outreach Website

With former UCLA undergraduate Erika Hoffman, Co-I Furlanetto released an outreach website (https://cosmicdawn.astro.ucla.edu/) highlighting the science of the first galaxies. The NESS/UCLA website highlights the key insights we hope to learn about the Cosmic Dawn and Dark Ages as well as the instruments that are studying it. This first version of the website is targeted toward the interested layperson (aiming for a Scientific American level). It allows exploration of the era on several levels, from quick summaries of the key science topics to in-depth exploration of some of the key observables. Lunar radio

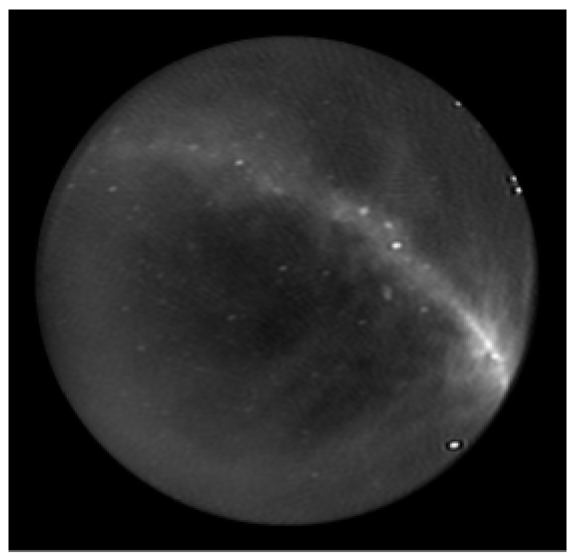

Fig. 9 - All-sky image with the OVRO-LWA, taken on January 12, 2022, from commissioning observations, as part of the ongoing upgrade of the array. At the time of these commissioning observations, just under half of the antennas were operational, all of which are in the central 200-m diameter "core" of the array. This image spans 34–84 MHz, with a spatial resolution of approximately 1 degree. The arc of diffuse emission crossing the center of the image is synchrotron emission from the Milky Way; the Sun can be seen setting towards the horizon in the bottom-right corner of the image.

observatories receive a special focus, with science pages discussing exotic physics during the Dark Ages, the formation of the first stars and black holes, and the 21-cm spin-flip background itself, as well as a page about low-frequency radio observatories and about telescopes on the Moon (Figure 10).

3.2. Planetarium Show: Forward! To the Moon

Fig. 10 - Screen shot of the NESS/UCLA outreach website on the early Universe and lunar radio telescopes.

NESS and the Fiske Planetarium at the University of Colorado, in collaboration with TEND Studio, SSERVI, and Lockheed Martin, will premiere a feature length, full dome film titled *Forward! To the Moon* at CU-Boulder in February 2022. This production features the NASA Artemis (Figure 11) 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. In addition to the Fiske premiere, special events are also being planned for the San Francisco Bay Area, Houston, Huntsville, and other locations. The film will be distributed for free to planetariums around the globe.

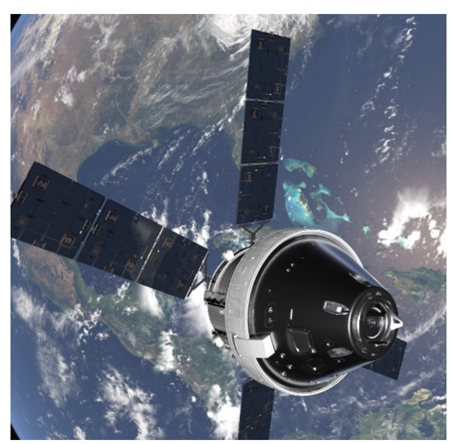

Fig. 11 - Frame from *Forward! To the Moon* illustrating Orion leaving Earth heading to the Moon.

3.3. Public Talks

- "Study for FARSIDE," *presented by Nivedita Mahesh,* East Valley Astronomy Club, Arizona. March 2021.
- "FARSIDE: Exploring the Cosmos from the Moon," *presented by Nivedita Mahesh***,** Saguaro Astronomy Club, Arizona. January 2022.
- Public talk to the Astronomy Club of Asheville, NC on "Taking Silicon Valley to the Moon," July 15, 2021, presented by Jack Burns.
- Public lecture to Secular Hub in Denver, "Taking Silicon Valley to the Moon," December 11, 2021, presented by Jack Burns.

4. Student/Early Career Participation

Undergraduate Students

1. Erika Hoffman (UCLA): outreach website designer
2. Anna Tsai (UCLA): theoretical 21-cm studies
3. Natsuko Yamaguchi (UCLA): theoretical 21-cm studies
4. Phaedra Curlin (University of Colorado Boulder): surface telerobotics
5. Mason Bell (University of Colorado Boulder): surface telerobotics
6. Madaline Muniz (CU-Boulder): surface telerobotics
7. Alexis Muniz (CU-Boulder): surface telerobotics

Graduate Students

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

Technicians

14. David Lewis (Arizona State University, part-time technician): experimental 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): theoretical 21-cm studies
19. Bang Nhan (National Radio Astronomy Observatory): experimental 21-cm studies
20. Keith Tauscher (University of Colorado Boulder, until July 2021): 21-cm data analysis studies

5. Mission Involvement

1. **SunRISE:** In the past year the Sun Radio Interferometer Experiment (SunRISE) mission passed its Integrated Design Review, a major milestone that led the mission into Phase C of operations, where implementation of the mission accelerates. 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.

2. **ROLSES:** This will be the first NASA-funded radio astronomy payload to land on the Moon as part of the first CLPS mission (using the Intuitive Machine (IM) NOVA-C commercial lander). One exciting recent development is that we will be able to observe for ~12 hrs during the lunar night at the end of the mission. IM has completed the so-called FlatSat testing twice, and the ROLSES NPLP was finally delivered to IM late in June 2021. The current NOVA-C lander launch date is in June 2022. The goals for this mission include: determine the photoelectron sheath density from ~1 to ~3 m above the lunar surface; demonstrate detection of solar, planetary, & other radio emission from lunar surface; measure reflection of incoming radio emission from lunar subsurface and below; measure Galactic spectrum at <30 MHz; aid in the development of lunar radio arrays. NESS Deputy PI MacDowall is PI of ROLSES, and Burns and W. Farrell (NESS collaborator) are Co-Is.

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. Work on further development of FARSIDE was described above. Burns is the PI and Hallinan is Deputy PI of the FARSIDE concept.

4. **LuSEE** (includes input from the NASA-funded DAPPER concept study): LuSEE is now fully funded by NASA, with partnership from DOE, as the first NASA radio astronomy payload for the lunar farside. It is scheduled by the NASA ESSIO office to fly as CS-3 on a separate lander, in conjunction with the deployment of a lunar comms satellite, in 2025. It will carry sufficient batteries to permit operations during the lunar night. This will enable the first truly sensitive observations of the 21-cm signal from the Dark Ages. Antenna and receiver designs continue to advance based, in part, on previously funded work by NESS. NESS Collaborator S. Bale is the PI of LuSEE, and Burns and MacDowall are Co-Is.

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 terrain digital elevation models of lunar sites (Hermite-A, Nobile, Shackleton Ridge). Fong also served on the Independent Assessment Team for the "Moon Ranger" lunar rover mission (SMD PRISM program), providing robotics expertise to the CDR and Delta CDR reviews.

6. Awards

Jack Burns was elected in 2021 to the International Academy of Astronautics, headquartered in Paris.

7. Equity, Diversity, Inclusion & Accessibility

Equity, diversity, inclusion, and accessibility are core values of the NESS team and our home institutions. Two EDIA initiatives were pursued by NESS in this past year. First, one of our goals is to increase women and minority participation in fields that have traditionally been underserved. Robotics is a prime example. In our NESS telerobotics lab, we have recruited three women, two of whom are persons of color (Fig. 6). All three are engineering majors. Phaedra Curlin was promoted in 2021 to Lab Manager. She is graduating this Spring and will begin graduate school at CU in the Fall. In addition, an astrophysics/instrumentation Ph.D. student at ASU supported by NESS and mentored by Co-I Bowman, Nivedita Mahesh, is graduating and will begin a postdoc this Fall at Caltech mentored by NESS Co-I Hallinan. Second, 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 shows a new generation of astronauts, many women and persons of color are 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. Our goal in this show that will be seen by tens of thousands in planetariums world-wide is that space careers are open to everyone.