NESS Team 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 deployment of low frequency radio antennas in the lunar/cis-lunar environment using surface telerobotics, for the purpose of cosmological measurements of exotic physics at the end of the Dark Ages, astrophysical measurements of the first luminous objects during Cosmic Dawn, radio emission from the Sun, and extrasolar space weather. NESS is developing instrumentation and a data analysis pipeline for the study of departures from standard cosmology in the early Universe and the first stars, galaxies and black holes, using radio telescopes shielded by the Moon on its farside. The design of an array of radio antennas at the lunar farside to investigate Cosmic Dawn, Heliophysics, and Extrasolar Space Weather 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 lunar surface facilitated by the planned Lunar Gateway in cis-lunar orbit. New experiments, using rover + robotic arms and Virtual/Augmented Reality simulations, are underway to guide the development of deployment strategies for low frequency antennas via telerobotics.

1. NESS Team Project reports

1.1. Low Latency Surface Telerobotics

The Telerobotics group at CU Boulder is composed of undergraduate and graduate students conducting laboratory-based and Virtual/Augmented Reality (VR/AR) experiments to explore various aspects of low-latency telerobotic operations for exploration on the Moon's surface.

1.1.1. Laboratory-Based Experiments

For the first experiment, our research goal was to explore operational constraints of low-latency telerobotics in the context of geological exploration on the Moon. In particular, we ran two lunar rover simulations to quantify the impact of decreased video frame-rate and increased communication latency on human operator performance. **Our results indicate that a threshold video frame-rate exists at 5 frames per second, and dropping below this frame-rate significantly decreases performance. We also found that operating at increased communication latency (2.6 seconds round-trip) increases the time to complete tasks by 150% when compared to real-time operation.** The results of our experiments were published in the IEEE Aerospace conference and will appear in Acta Astronautica (2019, in press). In 2018, our students presented talks on the results of our telerobotic geological exploration experiments at the Deep Space Gateway workshop and the IEEE Aerospace conference.

For the second experiment, our Telerobotics group has shifted our efforts to explore human situation awareness and cognitive load when performing low-latency telerobotic assembly tasks. A COTS robotic arm was integrated with a robotic mobile platform to conduct hardware-based simulations of the telerobotic assembly of a lunar radio array. In June, two students showed the progress made on the robotic arm at the Exploration Science Forum at NASA Ames. We are now preparing for a pilot experiment in which we aim to establish baselines for human situation awareness and cognitive load when using telerobotics to assemble a radio array.

Co-I Fong assisted with review and planning for the low-latency telerobotic assembly experiments that will be conducted by CU Boulder students. In particular, for telerobotic assembly studies, Fong provided advice and guidance on performance metrics (operator, task, and system). These studies are not intended to investigate fundamental human factors or human-robot interaction issues, for which there is extensive existing literature. Rather, the studies will focus on identifying core operational issues associated with the potential use of low-latency telerobotics for future human exploration.

1.1.2. Virtual/Augmented Reality Simulations

To help inform future planetary surface telerobotic research and operations, our team has explored the utilization of novel interfaces that utilize virtual reality (VR) and augmented reality (AR) technology to leverage the increased bandwidth afforded by the Lunar Gateway outpost. This work has taken the form of two projects: (1) the design of a rover VR simulation testbed; (2) an AR stereo video pass-through camera interface implemented on a physical robot for evaluating interfaces for surface assembly tasks.

Our VR simulation testbed was created for prototyping rover designs and surface teleoperation interfaces without the requirement of physical hardware. A VR head-mounted display (HMD) allows users to utilize immersive first-person control of the robot to simulate teleoperation of the robot on the lunar surface from space. The testbed enables exploration into the design of robot autonomy algorithms and new interfaces that support ground control, and/or crew operation (teleoperation and/or supervisory control) of surface robots from the Gateway to significantly improve critical NASA lunar exploration missions and enable a more rapid and iterative development process for surface telerobotics.

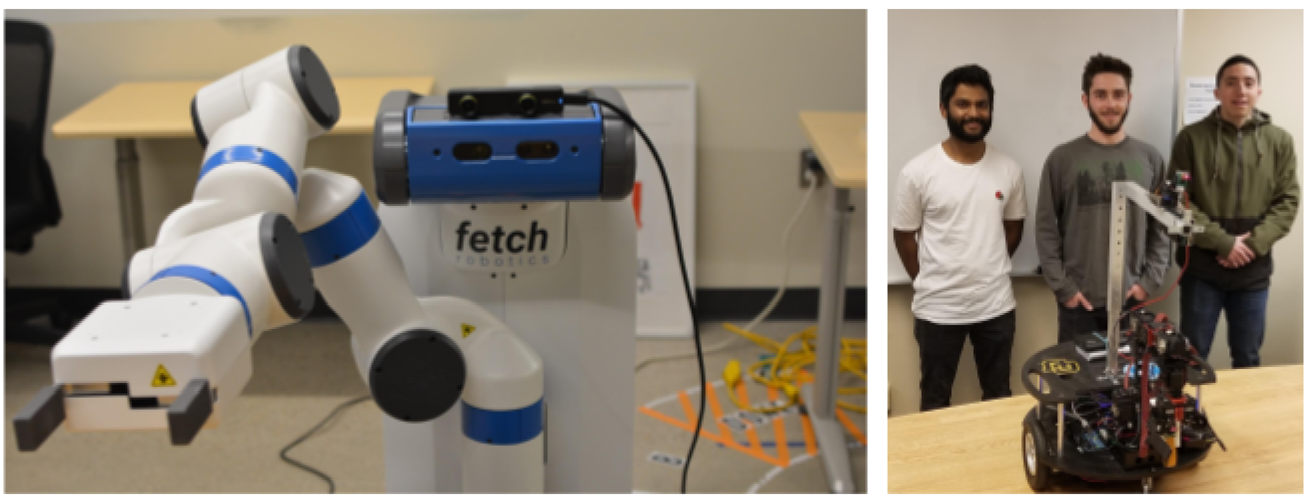


Figure 1: **(Left)** *A Fetch Mobile Manipulator robot with a 7-DOF arm utilized for simulating long-distance teleoperation assembly tasks. An AR stereo video pass-through camera is mounted to the head of the robot allowing the user to see from the robot's point-of-view while improving the remote user's depth perception with stereopsis.* **(Right)** *Arun Kumar (left), Ben Mellinkoff (middle), and Alexander Sandoval (right) representing the Telerobotics group along with a mobile rover and robotic arm platform for conducting low-latency assembly tasks.*

Additionally, to better inform interface design within the simulation testbed we implemented our own interface for the distal teleoperation of a real robot from within a VR HMD. As in the simulator, we provide the user with stereoscopic imagery that is streamed from an AR stereo video pass-through camera attached to the robot allowing the user to see from the robot's point-of-view. **Currently, we are evaluating the impact of depth perception on robot teleoperation assembly tasks, which is the first in a series of experiments aimed at informing future surface robot teleoperation tasks, such as radio relay assembly.** This work was done in collaboration with Jen Hellman's and David Kring's SSERVI teams and with NESS Co-I Terry Fong at NASA ARC.

To support development of the rover VR simulation testbed, Co-I Fong provided CU Boulder with a synthetic lunar terrain model developed by the Intelligent Robotics Group at the NASA Ames Research Center. The digital elevation model (DEM) covers a 1 km x 1 km area near the Hermite A crater. The

Figure 2: *Synthetic lunar digital elevation model of the terrain near Hermite A. The model has a resolution of approximately 4 cm/pixel (grid posting).*

synthetic DEM is based on publicly available images and laser altimetry that were acquired with the Lunar Reconnaissance Orbiter (LRO). This source data was used to generate an initial DEM with 1 m resolution using photoclinometry. The initial DEM was then synthetically enhanced via fractal synthesis to create artificial, high-resolution surface detail, which is consistent with lunar terrain morphology. In addition, rocks and synthetic craters were inserted into the DEM using a parametric shape model and using size-frequency distributions to control density.

1.2. Hydrogen Cosmology: Dark Ages, Cosmic Dawn and Epoch of Reionization

1.2.1. Instrument Design and Data Analysis Pipeline

This year, the CU Boulder group has further developed a global 21-cm spectrum data analysis pipeline —which originated in the work from the first year with DARE (Dark Ages Radio Explorer)— for the SmallSat mission concept DAPPER (Dark Ages Polarimeter PathfindER) led by NESS PI Burns. **We proposed for DAPPER in July 2018 as part of a new NASA Astrophysics Science SmallSat program and were awarded a NASA concept study in September.** Progress towards the proposal before, and the corresponding report afterwards, has occupied an important part of our activities. A fundamental difference between DARE and DAPPER is that the latter focuses on the lower-frequency (earlier times), purely cosmological trough of the Dark Ages, even though we also plan to sparsely sample the Cosmic Dawn trough as well (that DARE aimed to at higher frequencies). Two key fronts for this research have been the continuous development of the data pipeline and work on the ground-based precursor for DAPPER, the Cosmic Twilight Polarimeter (CTP) led by NESS Co-I Bradley at NRAO. The CTP also employs our same pipeline and thus serves as a valuable testbed for it. In addition, we have also been applying our pipeline to another key 21-cm instrument, EDGES (Experiment to Detect the Global Epoch-of-Reionization Signature; led by NESS Co-I Bowman), that in the beginning of 2018 reported a ground-breaking absorption feature at a frequency consistent with Cosmic Dawn (Bowman et al. 2018).

The analysis code *pylinex*[1] (Tauscher, Rapetti, Burns & Switzer, 2018), which performs fits to data using Singular Value Decomposition (SVD) and Information Criteria, continues to be extended to incorporate goodness-of-fit tests, including our newly defined psi-squared statistic[2] (Tauscher, Rapetti & Burns, 2018). The latter is an extension of the traditional chi-squared statistic that takes into account not only the values of the residuals but also the correlations between them. This allows for an augmented sensitivity to unfitted broad features even well within the noise level. We are also investigating a novel methodology to determine the validity of the training sets employed in the analysis. Starting with only those for the signal and the foreground, we are able to e.g. detect fine differences between sets generated by the 21-cm code ares[3] (Mirocha et al. 2012, 2014) and a parametric scheme

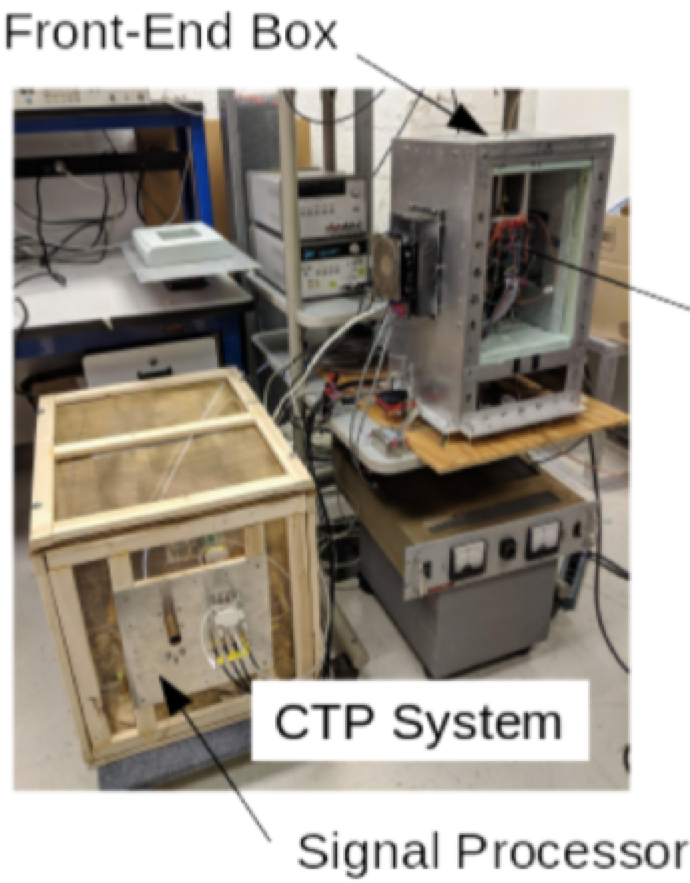


Figure 3: *Photographs of the upgraded CTP.* **(Left)** *Components that make up the CTP electronics.* **(Right)** *Close-up of the front-end module.*

(tanh; Harker et al. 2016) made to reproduce similar 21-cm models. We are also completing the pipeline by implementing the ability to transform the initial signal SVD estimates into physical parameter constraints in a Bayesian, simultaneous fit of these parameters together with those from the other components (foreground and instrument), as is paramount for extracting science at the end of our advanced measurement procedure.

[1] https://bitbucket.org/ktausch/pylinex
[2] https://bitbucket.org/ktausch/psipy
[3] https://bitbucket.org/mirochaj/ares

The ground-based Cosmic Twilight Polarimeter (CTP) led by NESS Co-I Bradley, a prototype for DAPPER, has undergone major upgrades this year. The electronics have had a battery of detailed laboratory measurements in an effort to understand the systematic issues limiting the sensitivity. A complete rework of the digital sampler and back-end signal processor which is now capable of handling 50 MHz of bandwidth with 8192 channels at a cadence of 2 seconds. In addition to the FFTs stage, the processor generates the coherence vector, average, variance, and spectral kurtosis via parallel spectrograph threads. This system was then used to analyze the RF electronics where careful integration tests revealed drifting in the tone calibration system traced to the square-law detector (SLD). An improved SLD is currently under development.

Further tests of the tone system for the CTP uncovered very weak gain modulation that was traced to the one microvolt level fluctuations in the power supply. Significant rework of the electronics packaging has removed ground loops and interference coupling that was affecting the operating conditions of the RF amplifiers. Finally, the two-stage thermal control system was replaced by a single-stage system having over five times the heat flow capacity to mitigate thermal drifts in the front-end electronics. At present, the rms error is under 100 mK with further improvements expected in the future. Figure 3 shows the components of the improved system.

In a study led by Co-I Bradley in collaboration with the CU Boulder team (Bradley, Tauscher, Rapetti & Burns, submitted to ApJ), we analyzed the recent EDGES data set (Bowman et al. 2018; see further details on this measurement below) utilizing a reported model of a ground plane artifact that could explain the unexpected EDGES results via this systematic effect instead of attributing them to an astrophysical origin. We find that the available evidence is inconclusive on whether the reported absorption trough is due to a ground plane artifact or an astrophysical signal.

1.2.2. <u>Low Radio Frequency Lunar Arrays</u>

In Fall 2018, NASA Astrophysics funded NESS to undertake a Probe-class concept study for a low frequency lunar array (FARSIDE = Farside Array for Radio Science Investigation of the Dark ages and Exoplanets). We are partnered with JPL's Team-X for this design study. As defined by Paul Hertz, a Probe instrument/observatory will have a cap of $1 billion. The P.I. for FARSIDE is Burns and Co-Is include NESS Co-Is G. Hallinan, J. Bowman, R. MacDowall, and R. Bradley.

As a start on this FARSIDE study, notional science traceability matrices (STMs) were developed for pathfinder and full-scale lunar arrays. Based on the STMs, preliminary steps for an array trade study were commenced. In order to inform the trade study, we began with an analysis of observing requirements for a shared-science objective array (heliophysics, exoplanets, cosmology) that established an allowed range of lunar farside latitudes for site selection. Over the last decade, the ground based 21-cm instrument community has advanced the requirements on array antenna design, particularly with respect to factors contributing to chromaticity in the response of the antennas. At the start of NESS, it was uncertain if dipole-based antennas placed directly on lunar regolith (such as the ROLSS concept) remained a viable antenna technology for the trade study. During this year, we began an investigation of the relevant antenna properties using the EDGES antenna as a reference design, but placed directly on lunar regolith. We found the efficiency of the antenna is only approximately 0.3 when placed on regolith, with a fractional bandwidth of about two, even for a relatively large dipole of approximately 2.5 x 4 meters. Slightly elevating the antenna above the regolith in a patch antenna-like design enabled the dipole size to be reduced to 1 x 1.5 meters while maintaining similar efficiency, but slightly smaller fractional bandwidth. We are presently investigating the chromatic beam patterns for pure regolith and other more-realistic trial conditions, including rocks mixed with regolith. We anticipate this work to be completed early in 2019.

1.2.3. Theoretical Predictions of the Global 21-cm Spectrum of Neutral Hydrogen

During this year, the UCLA team (led by Co-I Furlanetto) focused on developing the science case for highly-redshifted 21-cm observations from the lunar environment. Furlanetto's group has been building machinery to understand the signal both on its own and in the context of other measurements of the high-redshift universe. In Mebane et al. (2018), we built a new semi-analytic model of the very first "Population III" luminous sources to form in the Universe. This flexible, fast model allows us to predict the signatures of these stars and black holes under a wide variety of assumptions. In Mirocha et al. (2018), we examined whether these populations leave clear signatures on the 21-cm signals. **We found that, for some ranges of the parameters governing the formation of the first sources, they left a characteristic asymmetry in the 21-cm signal. Such a signature provides a clear target for future lunar radio arrays.**

The first claimed detection of the 21-cm signal by NESS Co-I J. Bowman (Bowman et al. 2018) has enormous implications for lunar instruments - and for the formation of the first stars. Mirocha & Furlanetto (2019) considered the implications of the EDGES measurement for galaxy formation, showing that it provided the first evidence that star formation in small, early galaxies must have been governed by different physics than local galaxies. We are currently continuing this investigation. Graduate student Mebane is applying our framework for the Population III sources to the EDGES signal, while undergraduate student Fu is considering globular clusters as a source population for the EDGES signal.

1.3. Extrasolar Space Weather

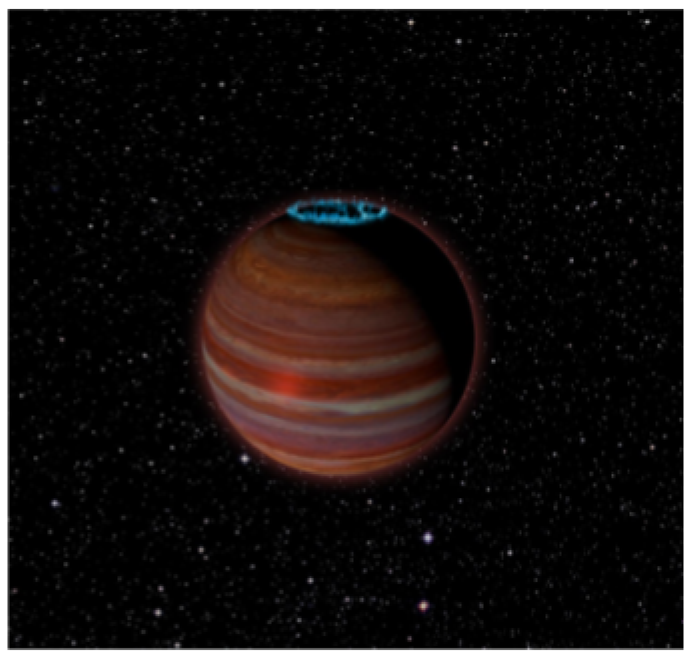


Figure 4: *Artist's impression of the auroral emission from the 12.7+/-1 Jupiter-mass free-floating object, SIMP J013656.5+093347.3.*

In the last year, the Caltech team (led by Co-I Hallinan) has focused on detection of planetary mass bodies at radio frequencies, as a proof of concept for a future lunar-based effort, while simultaneously constraining the science traceability matrix and associated design constraints for a lunar-based array. For the former, in a rather spectacular turn of events, one of our target brown dwarfs, which act as proxies for large exoplanets, the T2.5 dwarf SIMP J013656.5+093347.3, has recently been classified as a member of the Carina Near moving group, with a corresponding age of only 200 Myr (Gagné et al. 2017). This results in a mass of 12.7 ± 1 M_{Jup}, classifying the object as a possible free floating planet. Meanwhile the maximum magnetic field near the polar regions is at least 3000 G, based on constraints from our latest paper. By comparison, Jupiter's magnetic field is only 14 G at the poles. **This now becomes a critical new benchmark for dynamo theory, as well as the strongest candidate radio exoplanet to date.** Gaia DR2 should reveal other nearby free floating planet candidates via moving group association, so the next few years may be ripe for additional discoveries. Meanwhile, we have begun pushing into the Y dwarf regime with the VLA, initially with a small pilot sample (Kao et al. 2018a), followed by deep observations of 11 further objects in an ongoing observing program.

Simultaneously, we have completed the first extrasolar space weather surveys searching for radio signatures of stellar coronal mass ejections (CMEs) and extrasolar planetary magnetic fields. This involves 31 hours of data, monitoring 4000 stellar/planetary systems. Graduate student, and NESS team member, Marin Anderson will lead this paper in early 2019. This will serve as the framework for designing a similar survey from the lunar surface.

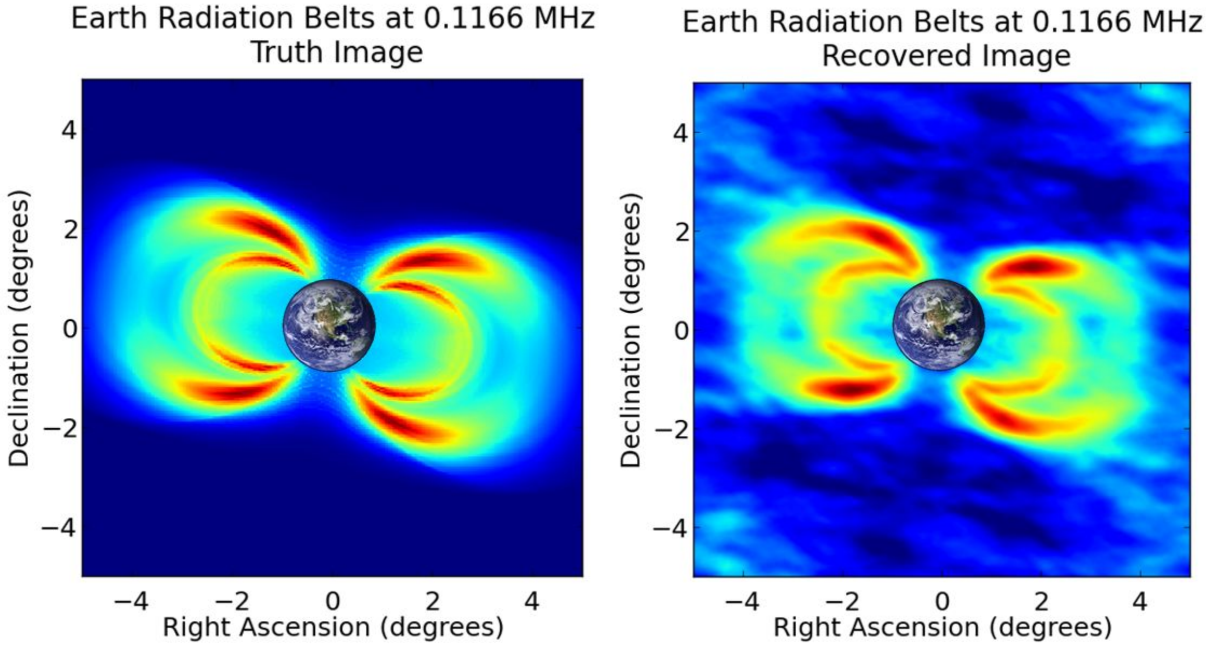
1.4. Heliophysics

As part of the Heliophysics and Space Physics key project of NESS, we are working with the Astrophysics key project personnel to design a lunar radio array pathfinder. Our NESS science goals for heliophysics are solved primarily by the capability to produce images of solar radio bursts at frequencies below the imaging possible by ground-based arrays. Typically, they cannot image solar radio bursts below frequencies around 20 MHz, which corresponds to the terrestrial ionospheric “cutoff” frequency. The electron density in the ionosphere blocks electromagnetic waves below a certain frequency and distorts the waves at frequencies above the “cutoff” frequency. The frequency of 20 MHz corresponds to solar radio burst emissions only a couple of solar radii from the solar surface, so ground-based observatory imaging only covers a small fraction of the inner heliosphere. **An array on the lunar surface will allow imaging down to frequencies of a fraction of 1 MHz, permitting tracking the solar radio bursts moving through space.** This imaging will provide improved data for scientific understanding of the burst physics and evolution, provide indications of magnetic field and density structures in the inner heliosphere, and contribute to space weather prediction. If the radio observatory could be in place before the end of the Parker Solar Probe mission (2018-2026), there would be considerable scientific overlap between to two missions.

The array that could address these goals could be on either side (near-side or far-side) because the solar bursts are more intense than the signals from astrophysics sources. So, we have proposed placing a radio array for solar burst imaging on the near-side, because that is easier to implement sooner, and because it could serve as a pathfinder for the far-side astrophysics array. It should be noted that the far-side array would also contribute to solar radio burst astronomy. **The Lunar Gateway will likely play a key role in the deployment of a far-side lunar surface radio array, transferal of the far-side data back to earth, and other aspects of the radio array operation.**

NESS Deputy and Co-I MacDowall led the submission of a response to the NASA Request for Information (RFI) for lunar-surface science payloads addressing "Low Frequency Radio Observations from the Near Side Lunar Surface." Related to this RFI response, he has led the submission of a NASA GSFC Center proposal to deliver a radio astronomy instrument to be carried to the lunar surface by a commercial lander. We have initiated various efforts to obtain NASA funding to advance the TRL of the low-frequency radio observatories to be built on the near-side and far-side lunar surface.

Co-I Kasper and his graduate student Alex Hegedus collaborated with members of the NOIRE team on a paper in preparation that takes simulations of the radiation belts and runs them through simulations of a lunar radio array. This work will end up in a sequence of papers exploring the range of radiation belt physics that could be detected by a Lunar nearside radio array. The below figures are a step towards this, showing the brightness of the radiation belts during a normal period (~10 Jy total from Lunar distances), and a dirty image recovered from a radio array centered on the sub-Earth point on the Lunar nearside.



2. Inter-team/International Collaborations

P.I. Burns and Assistant Director Rapetti are collaborating with NESS International Collaborators Falcke and Klein-Wolt towards employing an RFI analysis based on neural networks and the 21-cm data analysis pipeline being developed at the University of Colorado (CU) Boulder on data from the Netherlands-China Low-Frequency Explorer (NCLE). The latter is a low-frequency radio antenna developed in the Netherlands at Radboud University & ASTRON launched in the Chinese Chang'e 4 mission last May 2018 and currently orbiting around the Earth-Moon L2 point. The neural network RFI analysis is also being developed at CU Boulder in collaboration with researchers at INAF-Bologna, Julian Merten (also at Oxford University) and Massimo Meneghetti (also at the University of Bologna). We (the CU Boulder team) plan to then work with the Dutch collaborators to adapt both analyses (the pattern recognition pipeline and the neural network RFI removal procedure), primarily under construction for DAPPER, for the study of NCLE data. We intend to build training sets for uncalibrated beam and receiver systematics based on NCLE instrument and spacecraft information, as well as sets for RFI removal based on the expected characteristics of the internal and external RFI environment. In addition to the machine learning algorithms aforementioned, we will also utilize a number of novel statistical goodness-of-fit tools we have under development.

The code developed at UCLA by Co-I Furlanetto and his team will be used by the Hydrogen Epoch of Reionization Array (HERA) collaboration (PI: A. Parsons, University of California Berkeley), which includes South African, Canadian, and European collaborators, as part of their science interpretation program. Co-I Furlanetto is also a member of the Extragalactic Potential Observations (EXPO) Science Investigation Team for the WFIRST satellite project. As part of that project, Furlanetto is examining the synergies between galaxy surveys and low-frequency radio surveys, including those from the lunar environment.

Co-I Kasper visited the low frequency radio research groups at the Paris Observatory and Meudon, met with Baptist Cecconi (Paris Observatory, lead for the NOIRE low frequency mission concept study) and learned about the NOIRE mission concept study and simulation framework for radio emission from energetic electrons in the radiation belts that was developed by a research group in Toulouse. He also agreed to be informed about the status of the NOIRE project and concept study, and to work with them to determine if their framework could be used by him and his team instead of having to build separate simulations of the emission.

As described in section 1.1.2, CU Boulder NESS team members collaborated with Hellman's and Kring's SSERVI teams on robot teleoperation experiments within a VR HMD.

3. Public Engagement Report

We celebrated International Observe the Moon Night on October 20, 2018. International Observe the Moon Night is an annual worldwide public event that encourages observation, appreciation and understanding of our moon and its connection to NASA planetary science and exploration. The annual event connects scientists, educators and lunar enthusiasts from around the world. The Network for Exploration and Space Science, Fiske Planetarium, and Sommers-Bausch Observatory had activities planned throughout the evening, including: A public lecture entitled Our Future in Space: Humans, Robots, and Telescopes Exploring Together by Dr. Jack Burns at Fiske Planetarium and Telescope Observations of the Moon at Sommers-Bausch Observatory.

Burns presented "Our Future in Space" at Fiske Planetarium to 45 high school STEM students participating in the national Summer Science Program (SSP) at CU-Boulder on July 24, 2018. Burns, along with Scott Pace (Executive Director of the National Space Council), conducted a panel on Space Policy for the 60th anniversary alumni symposium of the SSP at CU-Boulder on July 28, 2018. Burns also presented "Our Future in Space: Humans, Robots, & Telescopes Exploring Together" at the Institute for Human & Machine Cognition 2018 conference in Pensacola, FL on February 22, 2018.

Harrison "Jack" Schmitt, an Apollo-era astronaut and the last person to set foot on the moon, gave a group of CU Boulder students the chance to see something rare: color on the lunar surface. Schmitt, who flew on Apollo 17 in 1972, visited the university on Monday, October 29, 2018. He spoke to an undergraduate class focusing on space science and policy and later delivered a public talk at the Fiske Planetarium that can be watched online.

NASA's Chief Scientist Dr. J. Green visited CU Boulder (11/28/2018) to lecture in Burns' Space Policy class, interacted with the local NESS team, and presented a seminar at LASP: "Space weather at Earth and Mars: How Bad Can it Get?". NASA ARC Director Dr. Eugene Tu visited CU (12/12/2018) to lecture in Burns' Space Policy class and met with the CU DAPPER team and other CU NESS members.

Early in the year, the breakthrough announced by EDGES (led by NESS Co-I Bowman), of an absorption trough at 78 MHz consistent with Cosmic Dawn but with an amplitude larger than possible in standard cosmology/astrophysics (suggesting exotic physics in the early Universe), generated abundant media attention. Find several links in the news section of the NESS website.

News stories about the telerobotics work led by Burns at CU Boulder appeared in the Boulder Daily Camera and CU Boulder Today at the end of January 2018 featuring undergraduate students B. Mellinkoff and M. Spydell.

4. Student/Early Career Participation

Undergraduate Students

1. Benjamin Mellinkoff (graduated during the year; now a masters student), University of Colorado Boulder, Surface telerobotics - Instrumentation.
2. Matthew Spydell (member only through the first part of the year), University of Colorado Boulder, Surface telerobotics - Instrumentation.
3. Alex Sandoval, University of Colorado Boulder, Surface telerobotics - Instrumentation.
4. Arun Kumar, University of Colorado Boulder, Surface telerobotics - Instrumentation.
5. Krista Fu (beginning 6/18), University of California Los Angeles, Astrophysics, Cosmic Dawn -Theory.

Graduate Students
6. Keith Tauscher, University of Colorado Boulder, Physics/Astrophysics, Cosmic Dawn – Theory / Data.
7. Bang Nhan (only through the first part of the year as student; afterwards as postdoc), University of Colorado Boulder, Astrophysics, Cosmic Dawn - Experiment.
6. Neil Bassett (from 6/18), University of Colorado Boulder, Physics/Astrophysics, Cosmic Dawn – Theory / Data.
8. Richard Mebane, University of California Los Angeles, Astrophysics, Cosmic Dawn -Theory.
9. Adam Trapp (beginning 10/18), University of California Los Angeles, Astrophysics, Cosmic Dawn -Theory.
10. Marin Anderson, California Institute of Technology, Astrophysics, Cosmic Dawn – Theory / Data.
11. Alex Hegedus, University of Michigan, Astrophysics, Heliophysics.
12. David Bordenave, University of Virginia, Astrophysics, Cosmic Dawn - Experiment.
13. Nivedita Mahesh, Arizona State University, Astrophysics, Cosmic Dawn - Experiment.
14. Michael Walker, University of Colorado Boulder, Surface telerobotics - Virtual Reality Telerobotics simulations.

Postdoctoral Fellows
15. Jordan Mirocha, University of California Los Angeles (through 8/18)/McGill University, Astrophysics, Cosmic Dawn - Theory.
16. Raul Monsalve, University of Colorado Boulder, Astrophysics, Cosmic Dawn – Experiment / Data.
17. Bang Nhan (second part of the year as postdoc), University of Virginia, Astrophysics, Cosmic Dawn - Experiment.
18. David Rapetti, University of Colorado Boulder / NASA Ames Research Center, Astrophysics, Cosmic Dawn – Theory/Data.

New Faculty Members
19. Jonathan Pober, Brown University, Astrophysics, Cosmic Dawn - Experiment / Theory.

5. Mission Involvement

DAPPER: In September 2018, NASA announced the selections for its first-ever competition for Astrophysics Science SmallSats. Among the missions funded for a concept study is one that the NESS team developed in collaboration with NASA Ames called the Dark Ages Polarimeter PathfindER (DAPPER). J. Burns is the P.I., R. Bradley is a Co-I, and a number of senior researchers, postdocs, and students from NESS are collaborators. DAPPER resulted in part from SSERVI-funded DARE (Dark Ages Radio Explorer) research.

DAPPER will explore, for the first time, the Dark Ages of the early Universe. After the Cosmic Microwave Background photons decoupled from baryons, the Dark Ages epoch began: density fluctuations imprinted from earlier times grew under the influence of gravity, eventually collapsing into the first stars and galaxies during the subsequent Cosmic Dawn. Exploring these early unobserved epochs, a key science goal of NASA, was demonstrated to be achievable by recent observations by the Experiment to Detect the Global Epoch of Reionization (EoR) Signature (EDGES).

In the early universe, most of the baryonic matter was in the form of neutral hydrogen (HI), detectable via its ground state's "spin-flip" transition. This line's rest frame frequency (wavelength) of 1420 MHz (21-cm) arrives today highly redshifted to low radio frequencies (<200 MHz) due to cosmic expansion. A measurement of the 21-cm spectrum maps the history of the HI gas through the Dark ages and Cosmic Dawn and up to EoR, when ionization of HI extinguished the signal. EDGES recently reported a 78 MHz (redshift $z\sim17$) absorption trough roughly consistent with that expected from Cosmic Dawn, but 3 times deeper than was thought possible from standard cosmology and adiabatic cooling of HI. Interactions between baryons and slightly-charged Dark Matter particles with a proton-like mass provide a potential explanation of this difference but other cooling mechanisms are also being investigated to explain these results.

The Cosmic Dawn trough is affected by cosmology and the complex astrophysical history of the first luminous objects. A trough representing the Dark Ages, predicted to occur at lower frequencies (higher z), however, is determined entirely by cosmological phenomena (including Dark Matter) that took place before star formation began. **DAPPER, acquiring data from low lunar orbit above the farside, will observe this pristine epoch (17-30 MHz; z~83-46), which is inaccessible from Earth due to ionospheric opacity.** DAPPER will measure the amplitude of the 21-cm spectrum to the level required to distinguish (at >5) the standard cosmological model from that of additional cooling derived from current EDGES results. In addition to Dark Matter properties such as annihilation, decay, temperature, and interactions, the low-frequency background radiation level can significantly modify this trough. Hence, this observation constitutes a powerful, clean probe of exotic physics in the Dark Ages. A secondary objective for DAPPER will be to verify the recent EDGES results for Cosmic Dawn, in the uncontaminated environment above the lunar farside, with sparse frequency sampling from 30-100 MHz (z~46-13).

The main challenge of this measurement is the removal of bright foregrounds. DAPPER is designed to overcome this by utilizing two pioneering techniques: (1) a polarimeter to measure both intrinsically polarized emission and polarization induced by the anisotropic foregrounds and large antenna beam to aid in the separation of the foregrounds from the isotropic, unpolarized global signal, and (2) a pattern recognition analysis pipeline based on well-characterized training sets of foregrounds from sky observations, instrument systematics from simulations and laboratory measurements, and signals from theoretical predictions. DAPPER team members recently demonstrated the effectiveness of dynamic polarimetry to measure foregrounds using the prototype Cosmic Twilight Polarimeter. Simulations using the DAPPER pattern recognition pipeline illustrate separation and detection of the standard signal, which has a minimal amplitude. Non-standard cooling would increase this amplitude, improving this measurement and pointing to new physics.

DAPPER's science instrument consists of dual orthogonal dipole antennas and a tone-injection receiver based on high TRL components from the Parker Solar Probe/FIELDS, CURIE, and WIND/WAVES. DAPPER will be deployed from NASA's Lunar Gateway and transfer to a stable 50x125 km lunar orbit to provide 5000 hrs of radio-quiet integration over a 2 year mission lifetime. Proximity to the Gateway offers a number of advantages such as regular ride-share transport, a fast communication system, a launch facility, and on-board data storage and computational equipment. DAPPER is a collaboration between the universities of Colorado-Boulder and California-Berkeley, the National Radio Astronomy Observatory, and the NASA Ames Research Center.

The concept study for DAPPER will be submitted to NASA on May 28, 2019. We expect to also submit a proposal on DAPPER to the Astrophysics Mission of Opportunity AO that will be due in August 2019.

SunRISE: The Sun Radio Interferometer Space Experiment (SunRISE) is a proposed NASA Heliophysics Explorer Mission of Opportunity that finished Phase A last year. **SunRISE will provide an entirely new view on particle acceleration and transport in the inner heliosphere by creating the first low radio frequency interferometer in space to localize heliospheric radio emissions.** Six small spacecraft (S/C) will fly in a supersynchronous geosynchronous Earth orbit (GEO) within about 10 km of each other and image the Sun in a portion of the spectrum that is blocked by the ionosphere and cannot be observed from Earth. Mission-enabling advances in software-defined radios and GPS navigation and timing, developed and flown over the past few years on the Mars Cube One (MarCO) and DARPA High Frequency Research (DHFR) missions, have finally made this concept affordable and low-risk. By determining the location of decametrichectometric (DH) radio bursts from 0.1 MHz–25 MHz, SunRISE provides key information on particle acceleration mechanisms associated with coronal mass ejections (CMEs) and the magnetic field topology from active regions into interplanetary space. SunRISE is highly complementary to current missions, such as Parker Solar Probe and Solar Orbiter, and to the ground-based Daniel K. Inouye Solar Telescope (DKIST).

SunRISE shows that an Explorer Mission of Opportunity can answer fundamental questions in heliophysics, with implications for space weather prediction, and serve as a pathfinder for small satellite missions that have the potential to revolutionize space science. **SunRISE will help us understand the particle acceleration that occurs throughout the cosmos and leads to solar flares, solar energetic particles (SEPs), anomalous cosmic rays, and Galactic cosmic rays (GCRs).** SEPs and GCRs can damage satellites and lead to radiation sickness (Schwadron et al. 2014). Without new measurement methods (Cucinotta et al. 2010; Schwadron et al. 2015), heliophysics is missing a cornerstone for understanding particle acceleration. Parker Solar Probe (Fox et al. 2016; Kasper et al. 2015) will fly within 10 RS but will not measure particles as they are first accelerated (~ 3 RS). SunRISE offers the solution: localize radio emission from acceleration source regions and by energetic particles as they travel interplanetary space, laying the observational foundation for understanding particle acceleration and transport physics at the nearest star.

The SunRISE investigation uses well-studied classes of DH radio bursts: Type II associated with CMEs and Type III from electrons escaping from active regions into the solar wind along open magnetic field lines. SunRISE measures the 3D location of source emission and its evolution in time by determining the emission frequency and angular location of the burst on the sky. SunRISE discriminates between competing hypotheses for the source mechanism of CME-associated SEPs by measuring the location of Type II emission relative to expanding CMEs over distances from 2 RS–20 RS (Objective 1), where the most intense acceleration occurs. Every major SEP event seen at Earth is associated with a Type II DH radio burst. Imaging a Type II burst constrains which major features of a CME are associated with SEP acceleration. SunRISE also determines if a broad magnetic connection between active regions and interplanetary space accounts for the longitudinal extent of flare and CME SEPs by imaging Type III bursts as they traverse the corona (Objective 2). SunRISE traces magnetic field topology from the corona into interplanetary space for the first time.

The theory and implementation of aperture synthesis is well developed for ground-based telescopes. The SunRISE observatory has three mission-enabling features: *Knowledge not Control*: The S/C positions do not need to be controlled to better than 1 km as long as they are known to ~ 1 m accuracy. *Integrated Solar DH Global Navigation Satellite System (GNSS) Receiver*: A Solar DH signal chain measures radio emission at the location of the S/C while a GNSS signal chain records signals from GNSS satellites in view. The GNSS signals are used on board to synchronize DH data collection and in ground-based precision orbit determination to provide accurate S/C location and time. There is no requirement for communication between S/C, which operate independently. *Correlator Architecture*: The DH-GNSS receiver transforms the received DH signals to the spectral domain. On the ground, the individual S/C data are combined to form SunRISE's synthetic aperture. This approach provides robustness against interference, reduces on-board computational complexity, and requires only modest downlink data volume. Implementation follows the proven approach of starting from well-defined, verifiable Level 1 science requirements that flow to Level 2 project requirements. A passive formation of six independent and identical S/C, SunRISE drifts in supersynchronous GEO orbit, high above the disruptive effects of the Earth's ionosphere.

The SunRISE baseline science mission requires five S/C. An extra S/C provides redundancy. Their orbits are designed to keep the formation within a maximum separation of about 10 km, while providing the interferometer baselines needed to sample a range of angular scales. Nearly all hardware and software designs have been used before in space. SunRISE integrates them into a 6U form factor, using a standard small satellite design to accommodate the DH-GNSS receiver, GNSS antennas and deployable dipole antennas.

A multi-channel polyphase filter bank processes the full spectrum from 0.1 MHz–25 MHz, allowing dynamic selection of a sufficient number of channels free from S/C generated or terrestrial interference to track radio emission over distances from 2 RS–20 RS. The P/L's 4-channel GNSS receiver can process up to 42 GNSS signals simultaneously, providing sub-meter position knowledge ($\lambda/15$ at the highest DH frequency) and time knowledge better than a few nanoseconds. In post-processing conducted on the ground, these GNSS observables precisely determine the position and time when the DH data were recorded, which are used to cross-multiply the signals coherently, forming a synthetic aperture with the required localization capability.

SunRISE is operated by JPL during its 12-month mission lifetime, employing existing tools that have been used for dozens of missions. Operations consist of regular data collection and orbit maintenance sequences occurring on a 2-week cycle. The science observing profile, with an observing availability greater than 90%, is sufficient to capture the typical duration of Type II bursts. Science data are accumulated continuously, with only brief interruptions for telecommunications, orbital correction maneuvers and reaction wheel desaturation. During data downlink, small orbital corrections are uplinked, if needed, to maintain the formation without risk of collision. SunRISE data flow from the S/C to the Deep Space Network to the JPL Mission Operations Center (MOC) to the University of Michigan (UM) Science Operations Center (SOC), and finally to the Space Physics Data Facility.

SunRISE will find out in the coming weeks if it is to be fully funded, and will launch in 2022 if it is.