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 astrophysical measurements of the first luminous objects in the early Universe, radio emission from the Sun, and extrasolar space weather. NESS is developing instrumentation and a data analysis pipeline for the study of 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 Deep Space Gateway in cis-lunar orbit. New experiments, using rover + robotic arms and Virtual Reality simulations, are underway to guide the development of deployment strategies for low frequency antennas via telerobotics.

1. NESS Team Project Report

1.1. Extrasolar space weather

Efforts on the extrasolar weather key project were executed largely on two fronts by Co-I Hallinan and his group:

i) VLA observations of brown dwarfs were used to push radio observations of substellar objects to lower masses culminating in the detection of radio emission from an object of mass 12.7 ± 1 M_{Jup}, right at the boundary between planets and brown dwarfs. This object is now the benchmark object for understanding dynamos in the mass gap between planets and stars. These observations confirmed magnetic field strengths of 3000 Gauss on this same object, orders of magnitude larger than predicted by theory for an object of this age (200 Myr) and mass.

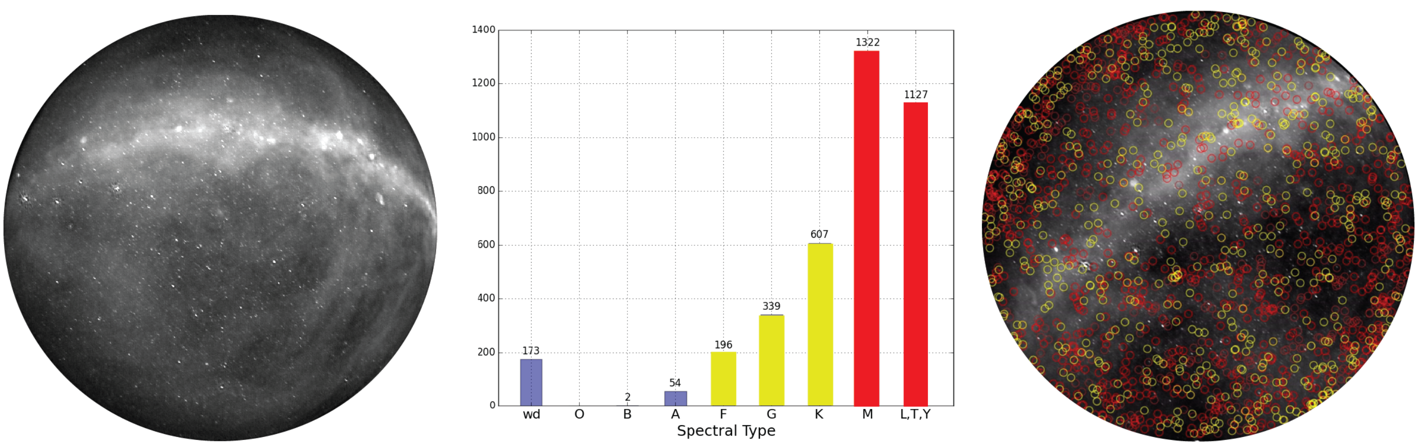


Figure 1: (Left) *A single 13-second snapshot integration using 224 antennas in the LWA core and the 32 antennas of the long-baseline demonstrator array (LBDA) detects >10,000 discrete extragalactic sources. The completed 352-antenna OVRO-LWA will detect >50,000 sources in each snapshot image.* **(Center)** *The spectral type distribution of the ~4,000 known stellar/planetary systems within 25 pc. The OVRO-LWA will continuously monitor each of these systems while above the horizon, corresponding to ~2,000 systems at any one time, with particular focus on systems potentially suitable for habitability (highlighted in yellow and red).* **(Right)** *A 13-second snapshot integration highlighting the location of the F, G and K type dwarf stars (yellow) and the M, L, T and Y dwarfs (red) above the horizon. Flux measurements are made at each location in each integration. Prime systems for regular detectable space weather events will be identified for prioritization with a lunar farside array, alongside the existing planned sample of Alpha and Proxima Centauri. This research is from Co-I Hallinan and his group.*

ii) Development continues of the OVRO-LWA, which serves as a pathfinder array for a future lunar farside experiment. This includes design development for the final stage of construction, anticipated to commence in late 2018, as well as early science with the current (Phase II) array. Early science involves monitoring observations of 4000 stellar systems in an effort to detect radio emission from both stellar CMEs and exoplanets. Study of this sample will help identify key targets for continuous monitoring with a lunar farside array. Light curves are generated in Stokes I and Stokes V, under the assumption that substantial circular polarization will be present in the case of many stellar and planetary bursts. This effort includes substantial effort to develop the capability for automated detection of enhancements in the radio light curves of this sample, to enable near real-time detection of extrasolar space weather events.

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

The 21-cm spin-flip line of neutral hydrogen provides a powerful method to study the currently unexplored end of the Dark Ages, Cosmic Dawn, and the beginning of the Epoch of Reionization. This signal from the early Universe is highly redshifted before it arrives to us as low-frequency radio waves. We plan to measure these signals from orbit above and on the surface of the lunar farside at night to avoid contamination from the Earth ionosphere, solar emissions, and human-generated radio frequency interferences.

1.2.1. Instrument design and data analysis pipeline development

In the first half year of NESS, we have worked on the design of mission concepts for low-frequency radio antennas shielded by the Moon (Dark Ages Radio Explorer; Dark Ages Polarimeter PathfindER), and the development of the corresponding data analysis pipeline. In Burns et al. (2017), we showed how the sky-averaged 21-cm spectrum can be measured, and the astrophysical parameters of the first stars and black holes constrained, in the presence of large foregrounds. We illustrated the ability to distinguish between two relevant physical models, one with primordial Population II stars (richer in metals) and the other containing also Population III stars (metal-poor). Our results rely strongly on the pioneering use of the polarization induced by the anisotropic foregrounds when interacting with the large beams of our antennas as described in Nhan, Bradley & Burns (2017), which facilitates the separation from the isotropic and thus unpolarized 21-cm signal. In Tauscher, Rapetti, Burns & Switzer (2018), we fully implemented this technique into the likelihood of our analysis, confirming the success we found before when this was only used as a prior. This paper also describes in detail the novel utilization of a pattern recognition algorithm in combination with information criteria, as well as rigorous statistical tests, to properly and efficiently extract the global 21-cm signal from systematics.

To experimentally demonstrate the validity of the induced polarization technique, which is to be employed later on in lunar orbit, Colorado graduate student Nhan, supervised by Co-I Bradley (NRAO) and Burns, deployed a prototype of the Cosmic Twilight Polarimeter. Observations were taken and a tentative detection of the periodic projection-induced polarization from the foreground spectrum was reported by Nhan et al. in a poster presented at the recent AAS meeting in Washington. For this presentation, Nhan was awarded an Honorable Mention Chambliss Prize.

1.2.2. Theoretical predictions of the 21-cm signal of neutral hydrogen

Another key component of this project is to provide theoretical descriptions of the 21-cm signal. One of the chief advantages of lunar or cis-lunar telescopes, relative to those on Earth, is their ability to explore the lowest radio frequencies, which correspond to the first luminous structures to form in the Universe. At UCLA, Co-I Furlanetto's group developed a theoretical framework for the formation and evolution of these early populations, which they submitted for publication in Fall 2017 (Mebane, Mirocha & Furlanetto, 2018). Their flexible, parameterized models allow efficient exploration of a wide range of physical prescriptions for this heretofore unobserved population. In Mirocha et al. 2018 (also submitted in the Fall), they further showed that these first generations of stars can exhibit *unique* signatures in the 21-cm background. Furlanetto's group is now exploring how these models impact spatial fluctuations in that background through semi-numeric and analytic models.

1.2.3. Trade Study of Low Radio Frequency Lunar Arrays

As part of the "Exploration Enables Astrophysics" key project within NESS, Co-Is Bowman, MacDowall, and Hallinan commenced a trade study of a lunar array prototype. Astronomical observatories on the lunar surface and in cis-lunar space have the potential to be amongst the most sensitive probes of the early Universe and habitability on Earth-like exoplanets. The requirements for these telescopes will push both technology boundaries and our knowledge of environmental effects at target destinations for human exploration. We initiated our efforts in Year 1 by investigating the compatibility of high-level science objectives across several astrophysical areas of study. We structured our investigation around the question "Can a single array perform Cosmic Dawn, heliophysics, and exoplanet science?" We found significant overlap in instrument requirements for angular resolution, spectral coverage, and sensitivity, particularly for the study of exoplanet habitability and 21-cm cosmology. Based on these findings, we initiated a trade study for a near-term pathfinder array able to achieve scientifically relevant advances in heliophysics, exoplanet space weather science, and demonstrate core technologies for a large array to target full-scale 21-cm science. By the end of the first six months of NESS, we completed a literature review of previous studies, collected relevant environmental information, and established a notional array for trade-off investigation and optimization.

1.3. Heliophysics

As part of the Heliophysics and Space Physics key project of NESS, we are working with the Astrophysics key project to design a lunar radio array pathfinder. The goal of this trade study is to develop a near-term pathfinder array that would address as many different scientific targets as possible. The ultimate goal of this effort is to develop hardware to be landed on the lunar surface by the commercial lander services that are now becoming available. For example, we have been in contact with the lander and rover provider Astrobotic Technology, Inc., to determine how to take advantage of the services that they provide.

Co-I MacDowall at GSFC has submitted a proposal to the NASA Heliophysics Technology and Instrument Development for Science (H-TIDeS) opportunity. The primary goal of this proposal is to increase the Technical Readiness Level (TRL) of a low-frequency radio observatory intended for location on the lunar surface. The motivation for this observatory is that it will use multiple antennas and aperture synthesis to image solar and other radio bursts at frequencies below the terrestrial ionospheric cutoff (~10 MHz). To date, such bursts have only been observed below 10 MHz with one or more spacecraft, permitting triangulation of the source locations as a function of frequency, but without imaging capability. We demonstrate that imaging will provide additional information about the bursts that will clarify the physics of the emission process. Imaging the radio bursts will also provide data relating to the environments of near-Sun missions like the Parker Solar Probe and Solar Orbiter. The images will also improve the application of the radio events to space weather prediction by refining the effective trajectories of the radio emitters. The mission hardware design will also contribute to future lunar radio observatories focused on various astrophysical sources – cosmology, exoplanet magnetospheres, etc. Funding obtained from a successful H-TIDeS proposal will be leveraged with the funding and activities of the NESS team.

Co-I Kasper and graduate student Alex Hegedus mainly worked on two tasks in support of the Heliophysics and Space Physics Key Project: simulation of radio array performance on the lunar surface, and simulation of diffuse emission from energetic electrons in the Earth's radiation belts. Low frequency radio array simulation code developed by Hegedus was extended to accommodate antennas placed in fixed locations on the lunar surface. The code can accept maps of diffuse emission on the sky and then simulate the antenna response as the Moon rotates and moves around the Earth and Sun, and images can be reconstructed. Maps of the surface of the Moon developed with Lunar Reconnaissance Orbiter (LRO) were used to identify several representative locations for Sun observing lunar radio arrays, both near the equator and at the poles, and several simulated solar observations were generated. Initial results were presented at the NASA Exploration Science Forum last summer and in the next year we look forward to using the code to help with the pathfinder trade studies.

Figure 2: *Close up view of the student-built COTS rover at the University of Colorado Boulder. The forward facing stationary camera is mounted at the front and the top camera is mounted on two servos for manipulation. The various electronics controlling the rover are housed underneath the white and black protective shields. The painted rocks are exploration targets for this teleoperated rover.*

1.4. Surface telerobotics

NASA plans to construct the "Deep Space Gateway" (DSG) in cis-lunar space early in the next decade. The proximity to the lunar surface allows for direct communication between the DSG and surface assets, which enables low-latency telerobotic exploration. One constraint associated with low-latency surface telerobotics is the bandwidth available between the orbiting command station and the ground assets. The bandwidth available will vary during operation. As a result, it is critical to quantify the operational video conditions required for effective exploration. CU undergraduates B. Mellinkoff and M. Spydell, under the direction of PI Burns, designed an experiment to quantify the threshold frame rate required for effective exploration.

The experiment simulated geological exploration via low-latency surface telerobotics using a modified commercial-off-the-shelf rover in a lunar analog environment. The results from this experiment indicate that humans should operate above a threshold frame rate of 5 frames per second. In a separate, but similar experiment, we introduced a 2.6 second delay in the video system. This delay recreated the latency conditions present when operating rovers on the lunar farside from an Earth-based command station. This time delay was compared to low-latency conditions for teleoperation at the DSG (≤0.4 seconds). The results from this experiment show a 150% increase in exploration time when the latency is increased to 2.6 seconds. This indicates that such a delay significantly complicates real-time exploration strategies. These results were reported as posters by Mellinkoff and by Spydell during the 2017 Exploration Science Forum and in a peer-reviewed IEEE Aerospace publication (Mellinkoff, Spydell, Bailey & Burns, 2018).

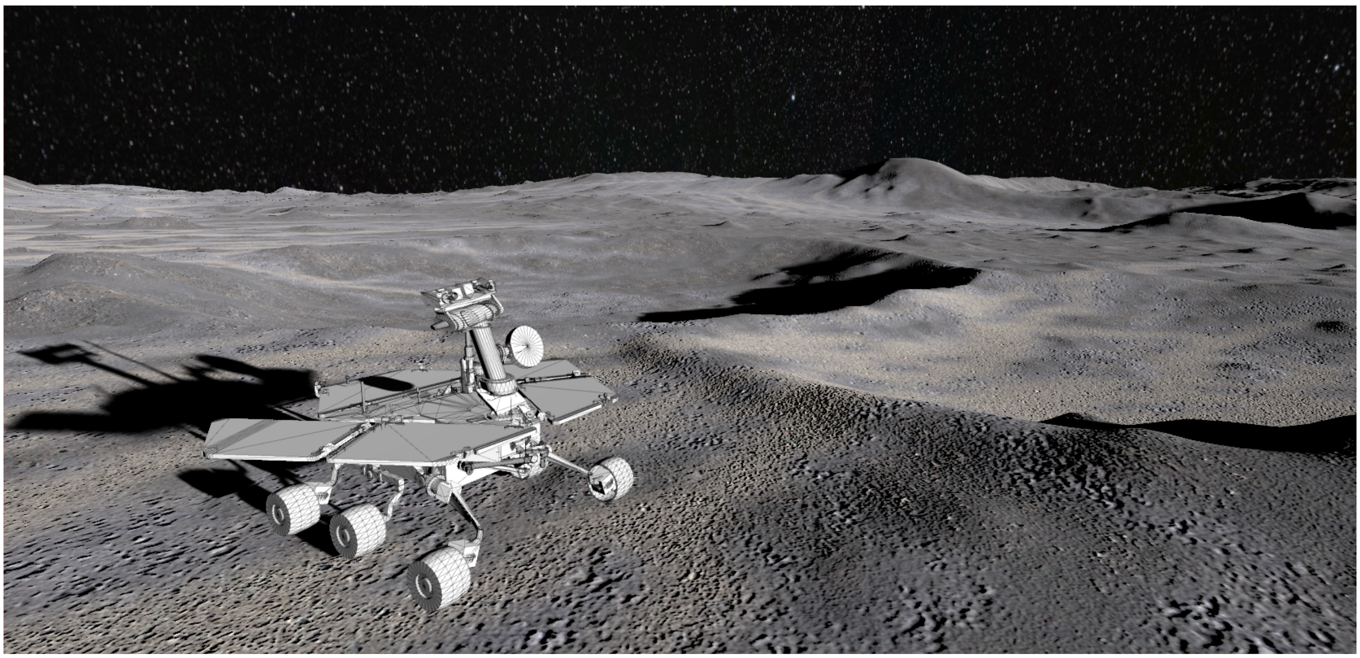


Figure 3: *Virtual rover and lunar surface as seen from a virtual reality head-mounted display. This experimental framework allows for 3rd and 1st person rover teleoperation for user studies, user training, and rapid prototyping of user interfaces and rover designs — all without the need of physical hardware.*

Collaborator D. Szafir, CU graduate student M. Walker, and Burns began to develop a virtual reality (VR) simulation testbed for prototyping lunar surface telerobotics. This experimental framework utilizes a VR head-mounted display to fully immerse users within a high-fidelity virtual lunar environment with realistic terrain and authentic rover design for real-time 3rd and 1st person teleoperation — all without the need of physical hardware. The simulation's robust physics and kinematics provide a platform for advancing algorithms that govern low-level robot autonomy and support interactive trade-offs between teleoperation and supervised control. This work has led to a new collaboration with Lockheed Martin to jointly explore the design of new interfaces that support ground control, and/or crew operation of surface robots from the Deep Space Gateway to significantly improve critical NASA lunar exploration missions. Recently, Co-I Fong provided a synthetically enhanced high-resolution lunar digital elevation model (DEM) that has been developed by NASA Ames for our NESS simulation, education, and public outreach activities. The DEM is based on publicly available images and laser altimetry of the Hermite A region that were acquired with the Lunar Reconnaissance Orbiter (LRO). The DEM covers a 1 km x 1 km area and includes artificial high-resolution detail (4 cm/pixel) including rocks and small craters.

References

Burns et al. (2017), ApJ, 844, 33

Nhan, Bradley & Burns (2017) ApJ, 836, 90
Tauscher, Rapetti, Burns & Switzer (2018), accepted in ApJ, arXiv:1711.03173
Mebane, Mirocha & Furlanetto (2018), submitted to MNRAS, arXiv:1710.02528
Mirocha et al. (2018), submitted to MNRAS, arXiv:1710.02530
Mellinkoff, Spydell, Bailey & Burns, 2018, in Proceedings of the IEEE Aerospace Conference, Big Sky, arXiv:1710.01254

2. Inter-team/International Collaborations

P.I. Burns and NESS Assistant Director Rapetti are developing an MOU with NESS International Collaborators Falcke and Klein-Wolt to work on adapting the 21-cm data analysis pipeline being developed at the University of Colorado (CU) Boulder to the Netherlands-China Low-Frequency Explorer (NCLE). The latter is a low-frequency radio antenna developed at Radboud University & ASTRON to be launched in the Chinese Chang'e 4 mission and orbit around the Earth-Moon L2 point in 2018. The plan is that the Dutch collaborators will supply the relevant instrument information to build training sets for the uncalibrated systematics of the beam and receiver as well as the expected characteristics of the data set to the CU Boulder team. Our team will then incorporate this input into the construction of an analysis pipeline for this instrument. For this purpose, the CU team will also perform simulations of the ability to separate systematics from the astrophysical foregrounds that in this case will be the signal to be studied. Together, we will in addition specifically work on developing analysis tools to properly remove the relatively strong radio frequency interference from Earth that is expected in the L2 environment. Currently, these techniques are planned to be based on machine learning algorithms such as neural networks, in addition to utilizing experimental design to benefit from the differences in behavior as a function of time between signal and systematics.

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 and European collaborators.

Co-I Fong visited CU Boulder in December 2017, met with students and researchers there, provided feedback on current research activities, and participated in a collaborative meeting between CU and Lockheed Martin members as well as Fiske Planetarium staff and a filmmaker to plan the production of a Planetarium show for the return of human exploration of the Moon.

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.

3. Public Engagement (including EPO) Report

The event *International Observe the Moon Night* was held at the Fiske Planetarium and Sommers-Bausch Observatory (SBO) on the CU Boulder campus. This 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 the following activities throughout the evening: the planetarium show "Back to the Moon for Good" at Fiske, telescope observations of the Moon at SBO, and the show "Dark Side of the Moon Laser Floyd" at Fiske. Members of NESS including Monsalve, Mellinkoff and Rapetti contributed to these activities by attending questions from the public.

In December 2017, PI Burns was interviewed on '*The Inquiry*' BBC radio program about space and lunar exploration in the episode titled How Do We Rule The Universe? On the same month, Burns was also interviewed about this theme by the American Institute of Aeronautics and Astronautics, in an interview that is to be published in 2018.

4. Student/Early Career Participation

Undergraduate Students

1. Benjamin, Mellinkoff, University of Colorado Boulder, Surface telerobotics - Instrumentation.
2. Matthew, Spydell, University of Colorado Boulder, Surface telerobotics - Instrumentation.
3. Alex Sandoval, University of Colorado Boulder, Surface telerobotics - Instrumentation.

Graduate Students

4. Keith Tauscher, University of Colorado Boulder, Physics/Astrophysics, Cosmic Dawn – Theory / Data.
5. Bang Nhan, University of Colorado Boulder, Astrophysics, Cosmic Dawn - Experiment.
6. Richard Mebane, University of California Los Angeles, Astrophysics, Cosmic Dawn -Theory.
7. Marin Anderson, California Institute of Technology, Astrophysics, Cosmic Dawn – Theory / Data.
8. Alex Hegedus, University of Michigan, Astrophysics, Heliophysics.
9. Janelle Holmes, University of Michigan, Astrophysics, Heliophysics.
10. David Bordenave, University of Virginia, Astrophysics, Cosmic Dawn - Experiment.
11. Nivedita Mahesh, Arizona State University, Astrophysics, Cosmic Dawn - Experiment.
12. Michael Walker, University of Colorado Boulder, Surface telerobotics - Virtual Reality Telerobotics simulations.

Postdoctoral Fellows

13. Jordan Mirocha, University of California Los Angeles, Astrophysics, Cosmic Dawn - Theory.
14. Raul Monsalve, University of Colorado Boulder, Astrophysics, Cosmic Dawn – Experiment / Data.
15. David Rapetti, University of Colorado Boulder / NASA Ames Research Center, Astrophysics, Cosmic Dawn – Theory/Data.

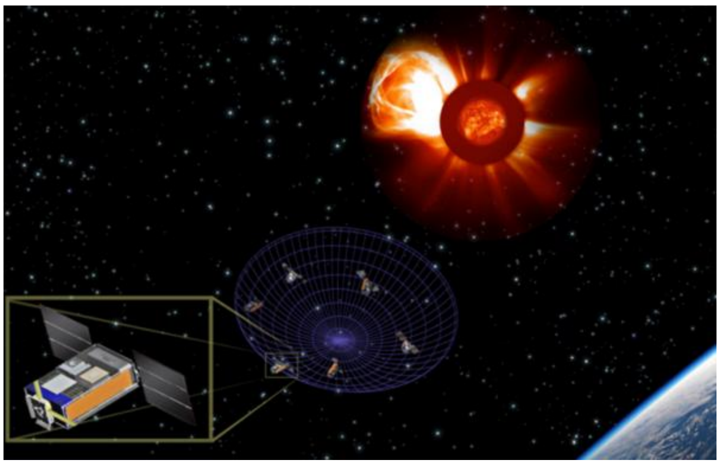
Junior Faculty Members

16. Daniel Szafir, University of Colorado Boulder, Surface Telerobotics - Virtual reality.
17. Gregg Hallinan, California Institute of Technology, Astrophysics, Cosmic Dawn – Theory / Data / Experiment.

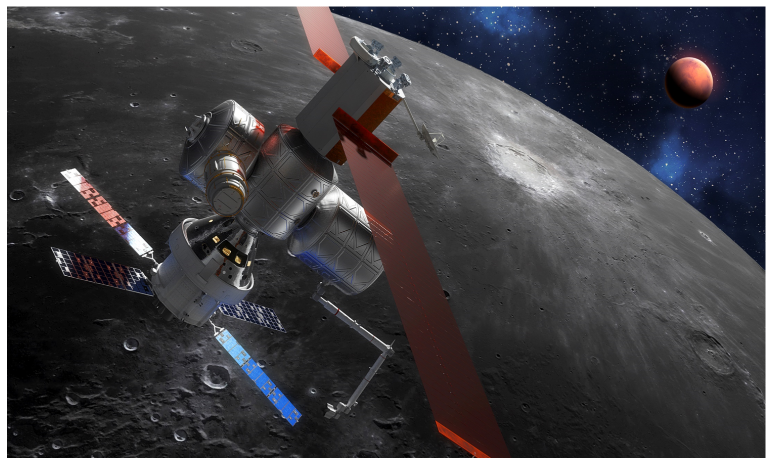
5. Mission Involvement

1. Justin Kasper, active missions within last decade: Parker Solar Probe SWEAP PI, 2018 launch; Wind mission Faraday Cup lead, 1994 launch; DSCOVR mission Faraday Cup lead, 2015 launch; LRO Co-I CRATER Project Scientist, 2009 launch
2. Justin Kasper, missions under development: SunRISE PI, in Phase A concept study; Europa Clipper Co-I, in development NET 2022 launch

3. Robert MacDowall, active missions: RBSP magnetometer, Wind/WAVES, STEREO WAVES, Parker Solar Probe
4. Sun Radio Interferometer Space Experiment (SunRISE), Justin Kasper (PI), Robert MacDowall, Alex Hegedus
5. NASA Resource Prospector, Terry Fong (Deputy Rover Lead)
6. Netherlands-China Low-Frequency Explorer (NCLE), Heino Falcke (PI), Mark Klein Wolt
7. Deep Space Gateway (DSG, Lockheed Martin), Scott Norris, Tim Cichan, Joshua Hopkins, Chris Norman
8. Dark Ages Radio Explorer (DARE), Jack Burns (PI), David Rapetti, Keith Tauscher, Raul Monsalve, Jordan Mirocha, Richard Bradley, Bang Nhan, Steven Furlanetto, Robert MacDowall, Judd Bowman, Justin Kasper, William Purcell, Dayton Jones
9. Dark Ages Polarimeter PathfindER (DAPPER), Jack Burns (PI), David Rapetti, Keith Tauscher, Raul Monsalve, Jordan Mirocha, Richard Bradley, Steven Furlanetto, Robert MacDowall, Judd Bowman, Justin Kasper, Dayton Jones



The Sun Radio Interferometer Space Experiment (SunRISE) was recently selected for a Phase A study as a Heliophysics Explorer Mission of Opportunity. Consisting of six small spacecraft spread over 10 km slightly above geosynchronous orbit, SunRISE will image bright solar radio bursts to track the origin and transport of solar energetic particles.



The planned Deep Space Gateway (DSG) will perform science from cis-lunar orbit, establish a lunar commercial economy, and provide a testing platform for destinations such as the surface of the Moon, asteroids and Mars. NESS investigates fastening a low-frequency radio antenna to the DSG for Cosmic Dawn studies and deploying an array of such antennas and purpose on the lunar surface using telerobotics from the DSG. Image courtesy of Lockheed Martin.